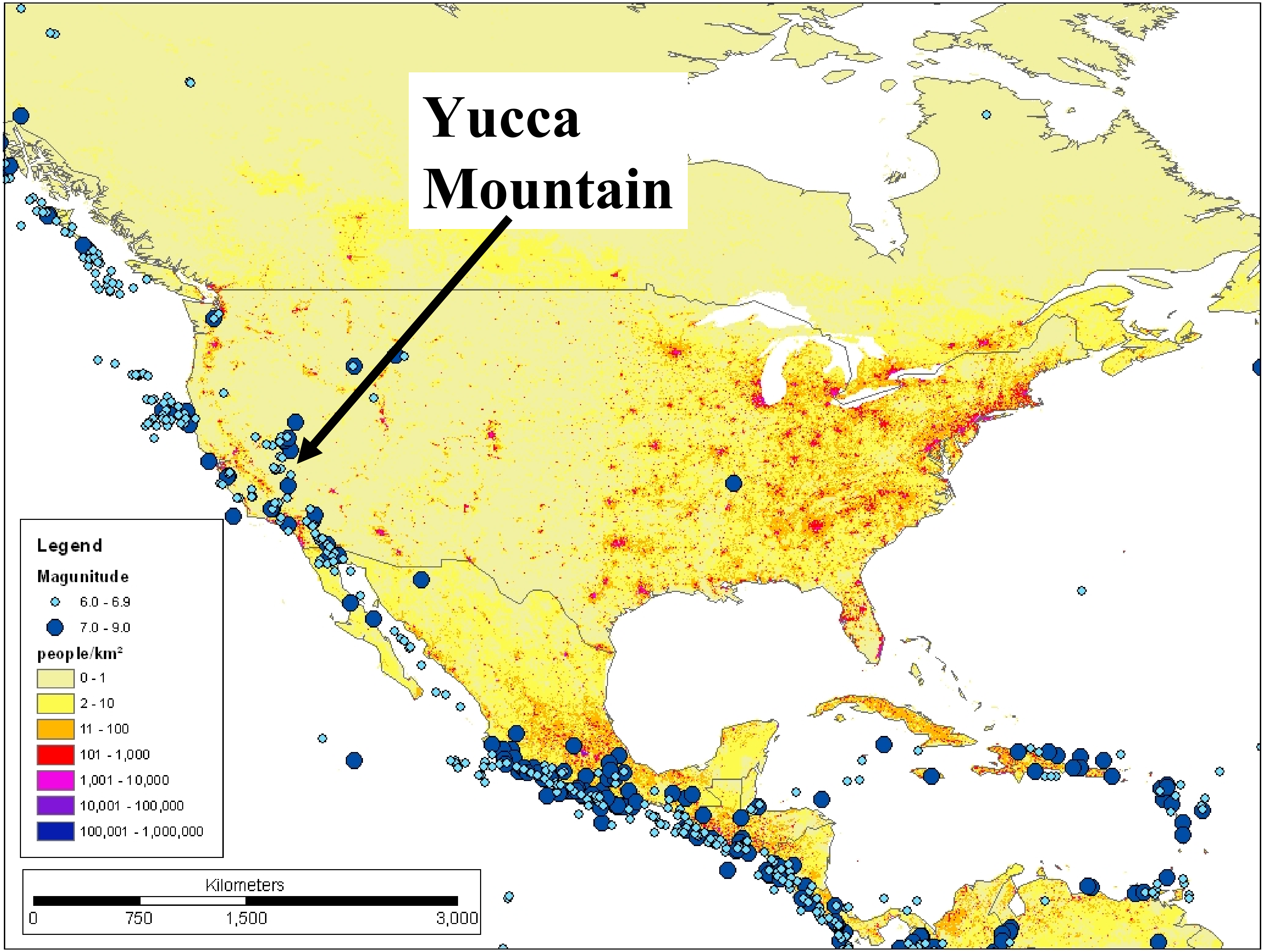
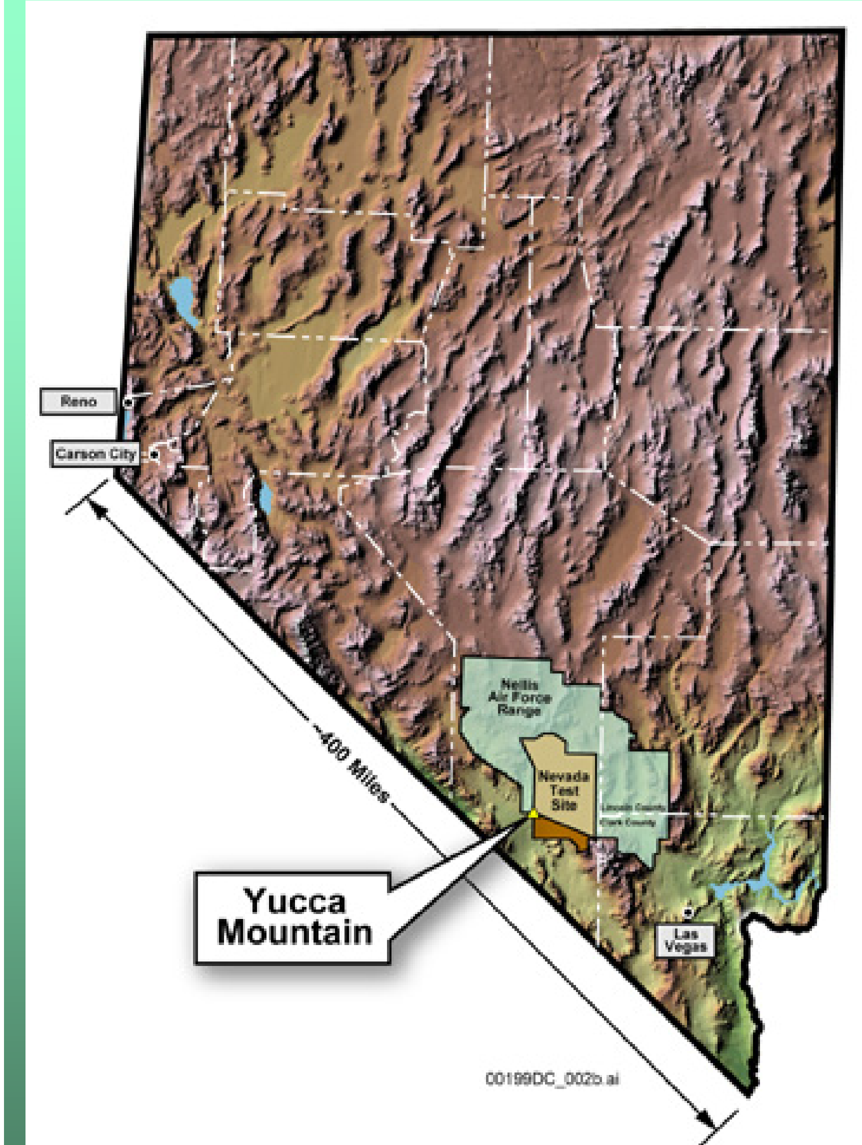
Role of Advanced Simulations to Improve Probabilistic Seismic Hazard Analysis

Advanced Simulations: A Critical Tool for Future Nuclear Fuel Cycles
Lawrence Livermore National Laboratory
December 14, 2005

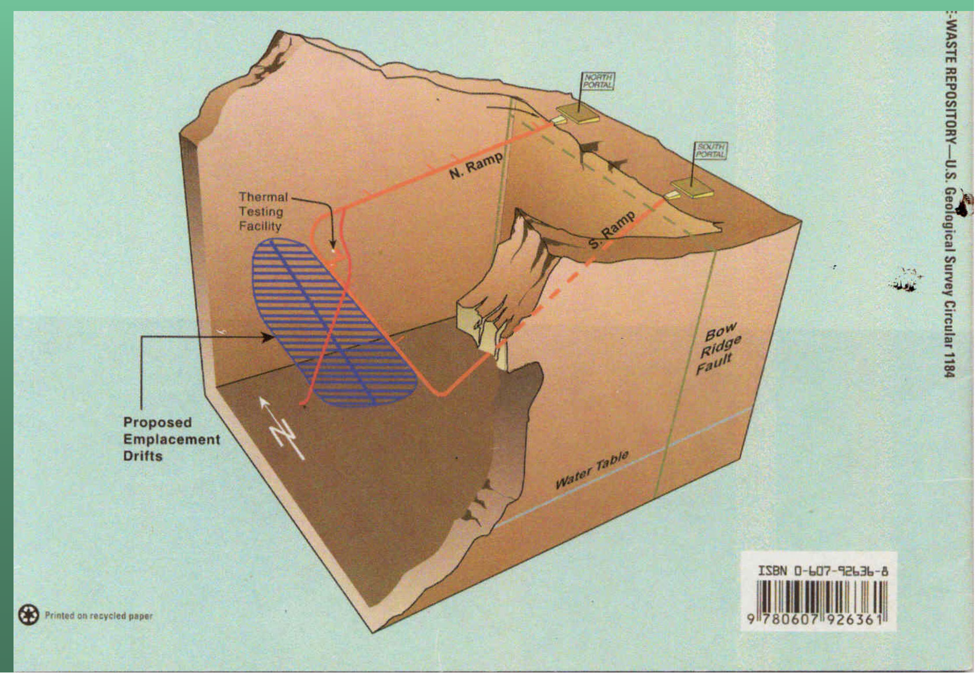
John Anderson

Nevada Seismological Laboratory

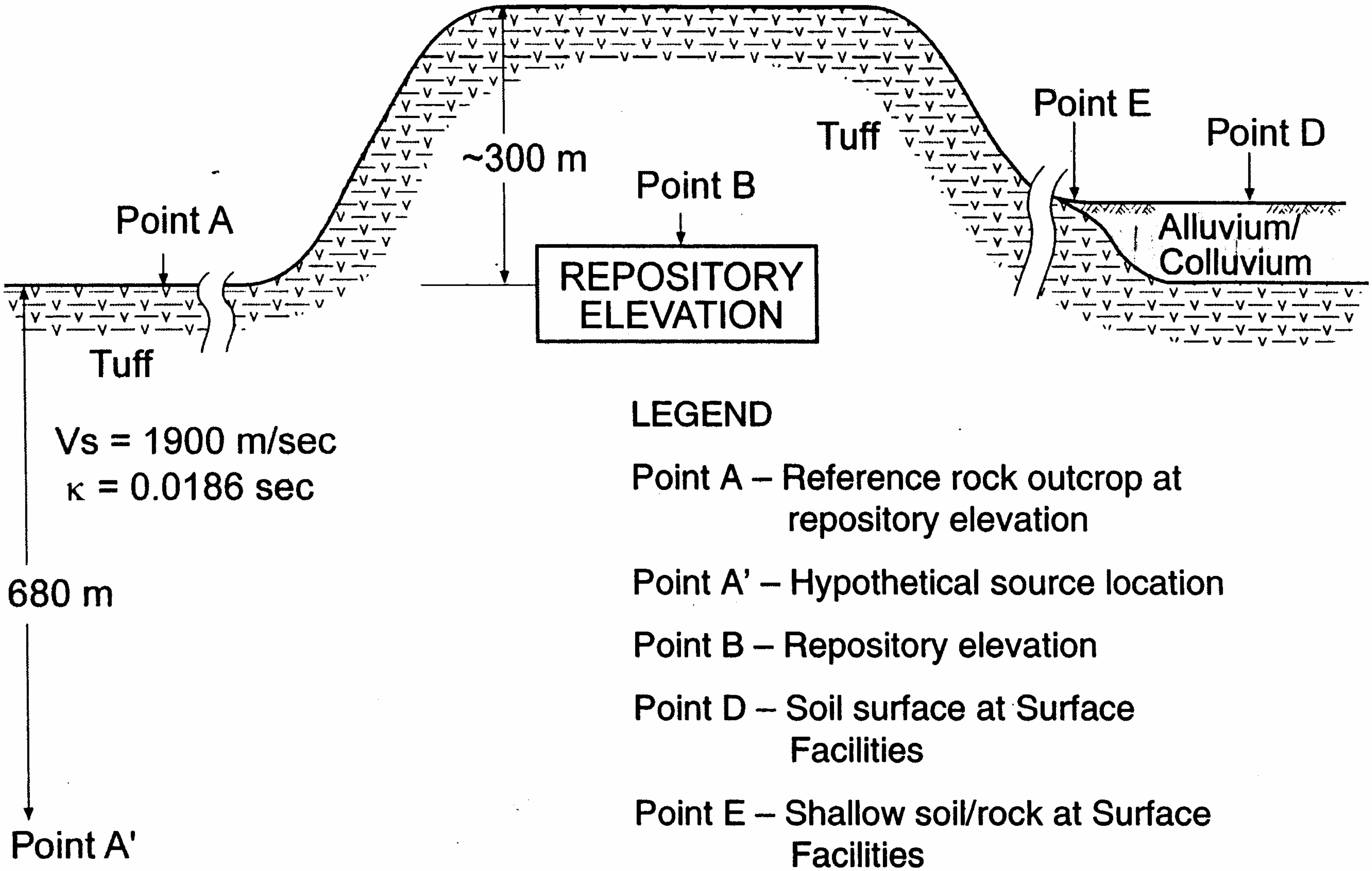

Yucca Mountain
Legend
Magunitude
6.0 - 6.9
7.0 - 9.0
people/km²
0 - 1
2 - 10
11 - 100
101 - 1,000
1,001 - 10,000
10,001 - 100,000
100,001 - 1,000,000
Kilometers
0
750
1,500
3,000


Reno
Carson City
~400 Miles
Nellis Air Force Range
Nevada Test Site
Lincoln County
Clark County
Yucca Mountain
Las Vegas
00199DC_002b.ai


Yucca Mountain
00199DC_043.ai


NORTH PORTAL
SOUTH PORTAL
N. Ramp
S. Ramp
Thermal Testing Facility
Proposed Emplacement Drifts
Bow Ridge Fault
Water Table
N
WASTE REPOSITORY—U.S. Geological Survey Circular 1184
ISBN 0-607-92636-8
Printed on recycled paper

Locations



LEGEND

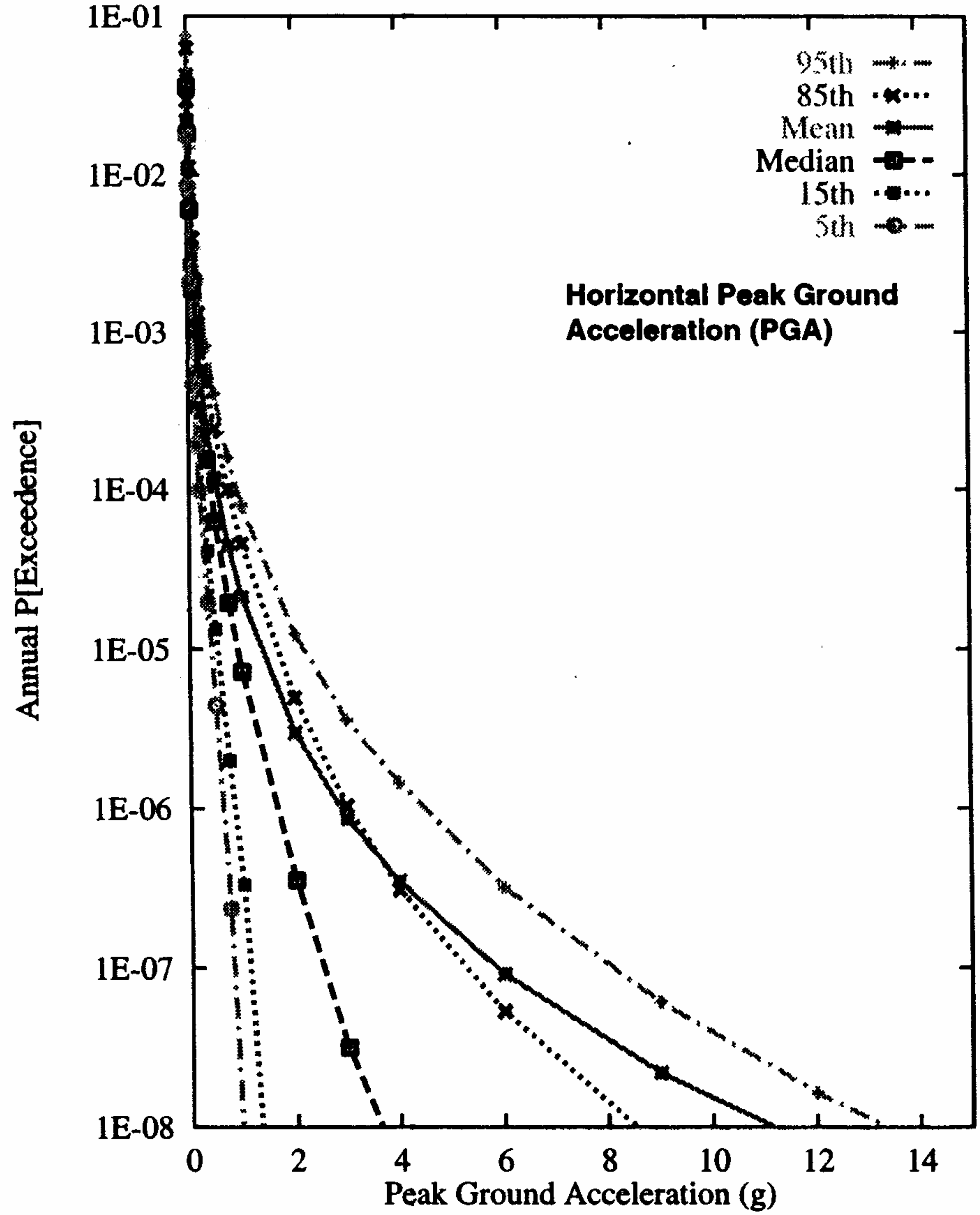
Point A – Reference rock outcrop at repository elevation

Point A' – Hypothetical source location

Point B – Repository elevation

Point D – Soil surface at Surface Facilities

Point E – Shallow soil/rock at Surface Facilities



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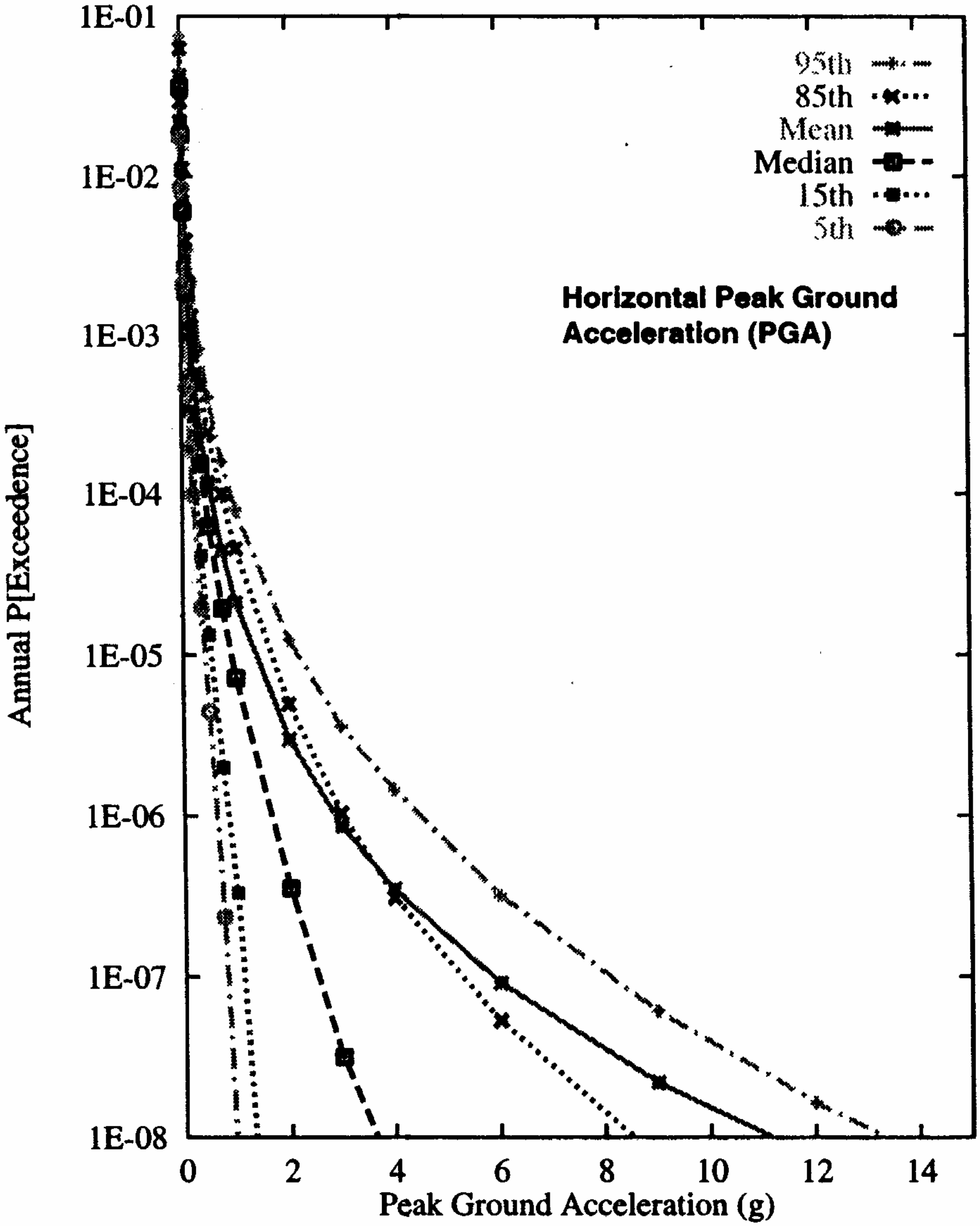

Regulatory concern: Events with probability 10^{-4} in 10^{4} years.

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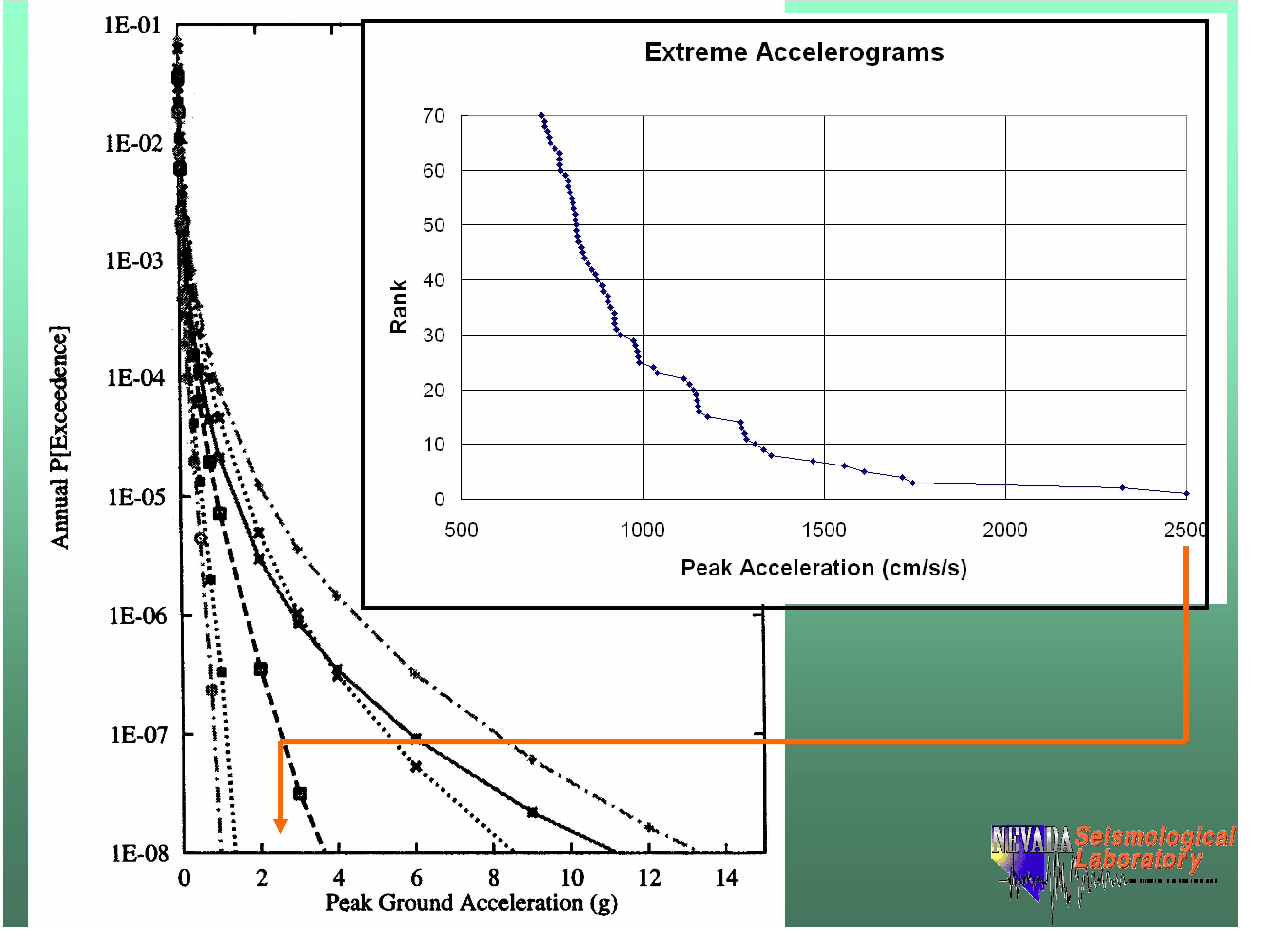

Extreme Accelerograms
Rank
Peak Acceleration (cm/s/s)
70
60
50
40
30
20
10
0
500
1000
1500
2000
2500
Annual P[Exceedence]
Peak Ground Acceleration (g)
1E-01
1E-02
1E-03
1E-04
1E-05
1E-06
1E-07
1E-08
0
2
4
6
8
10
12
14
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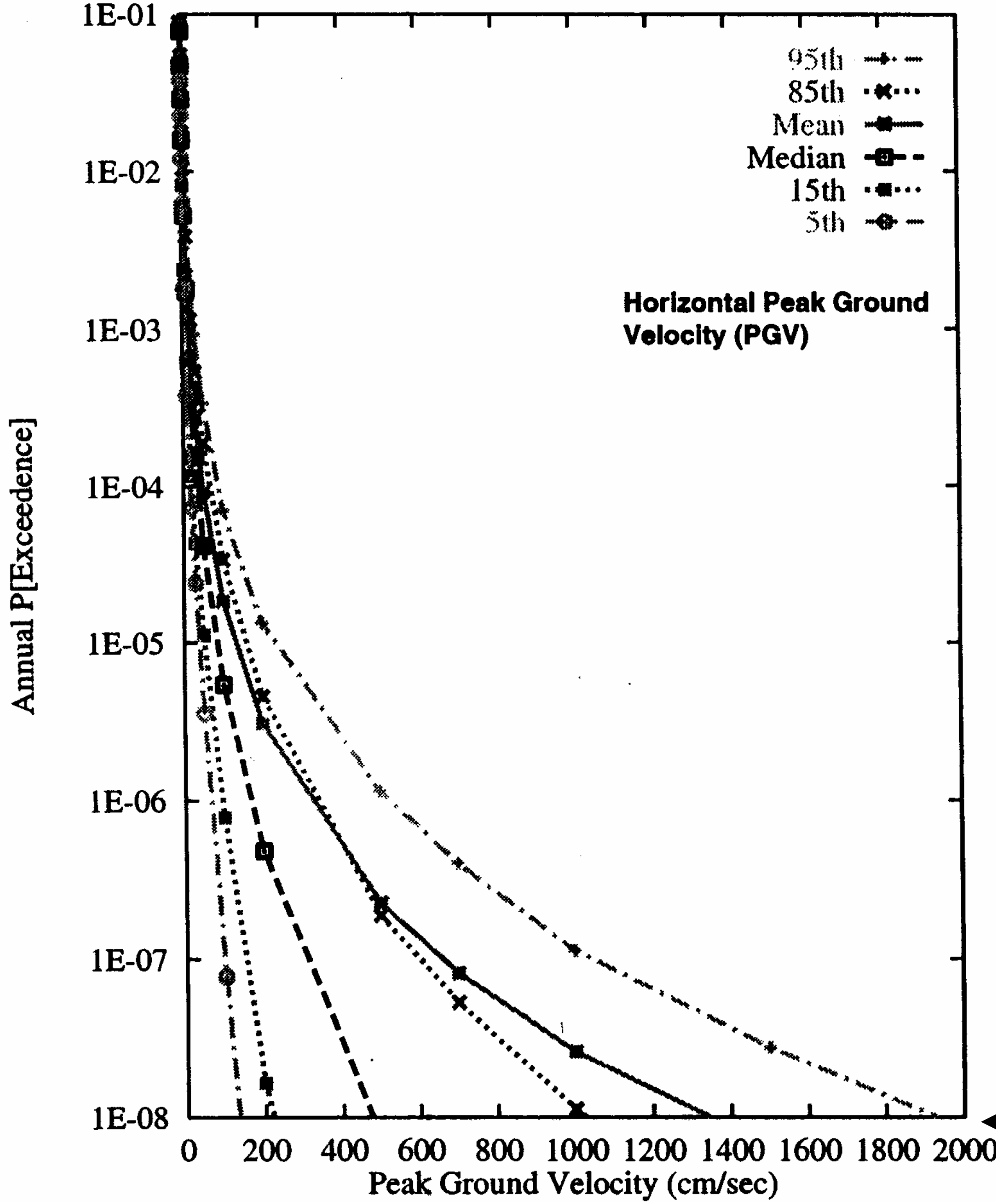

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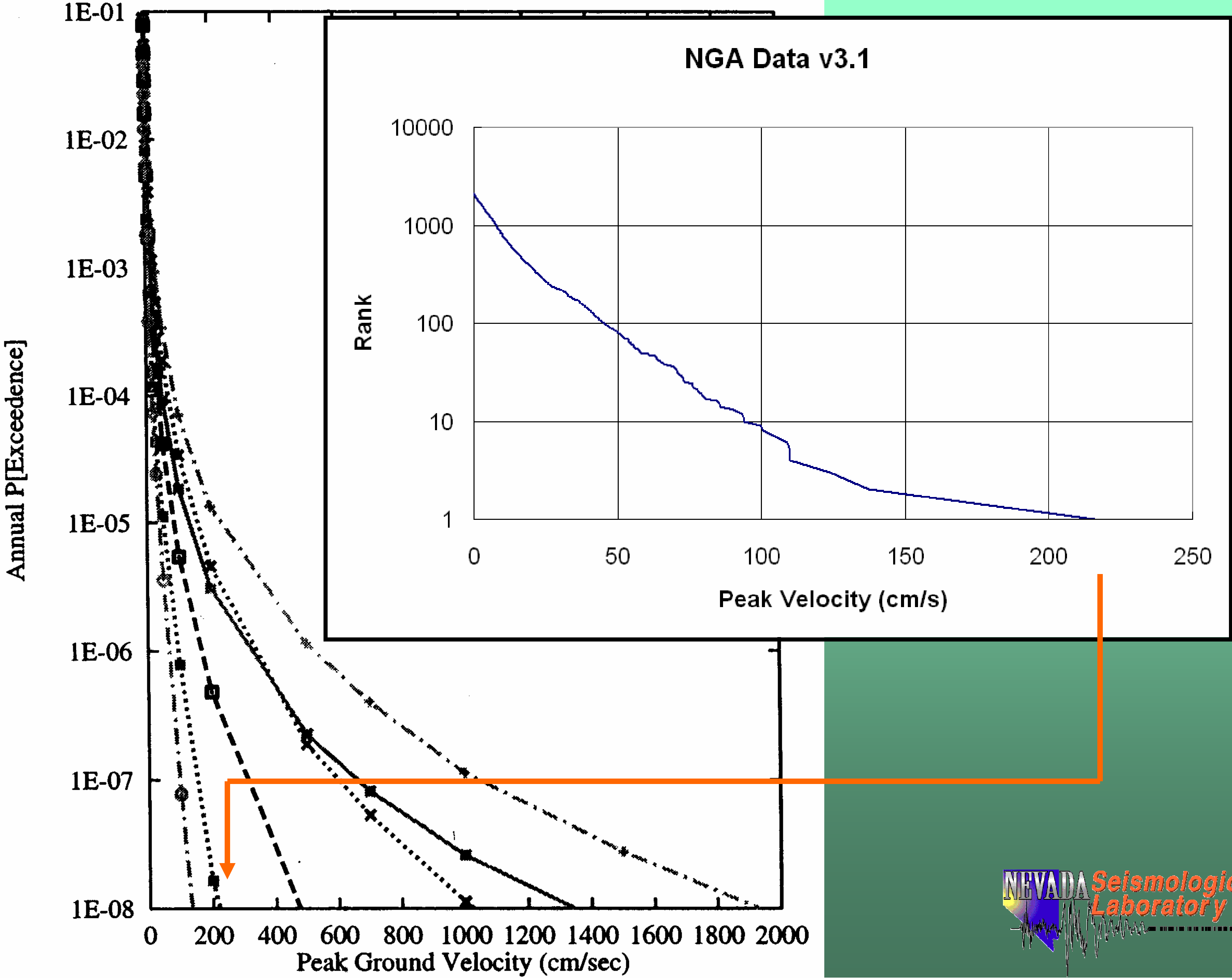

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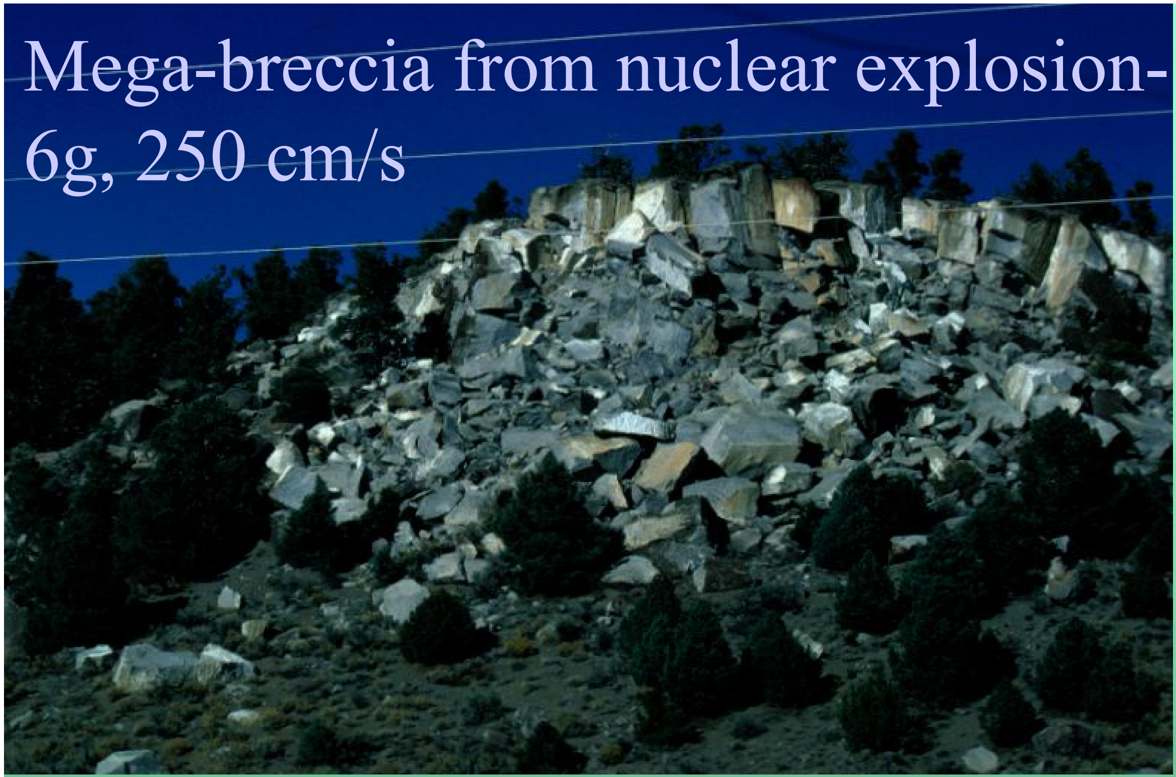
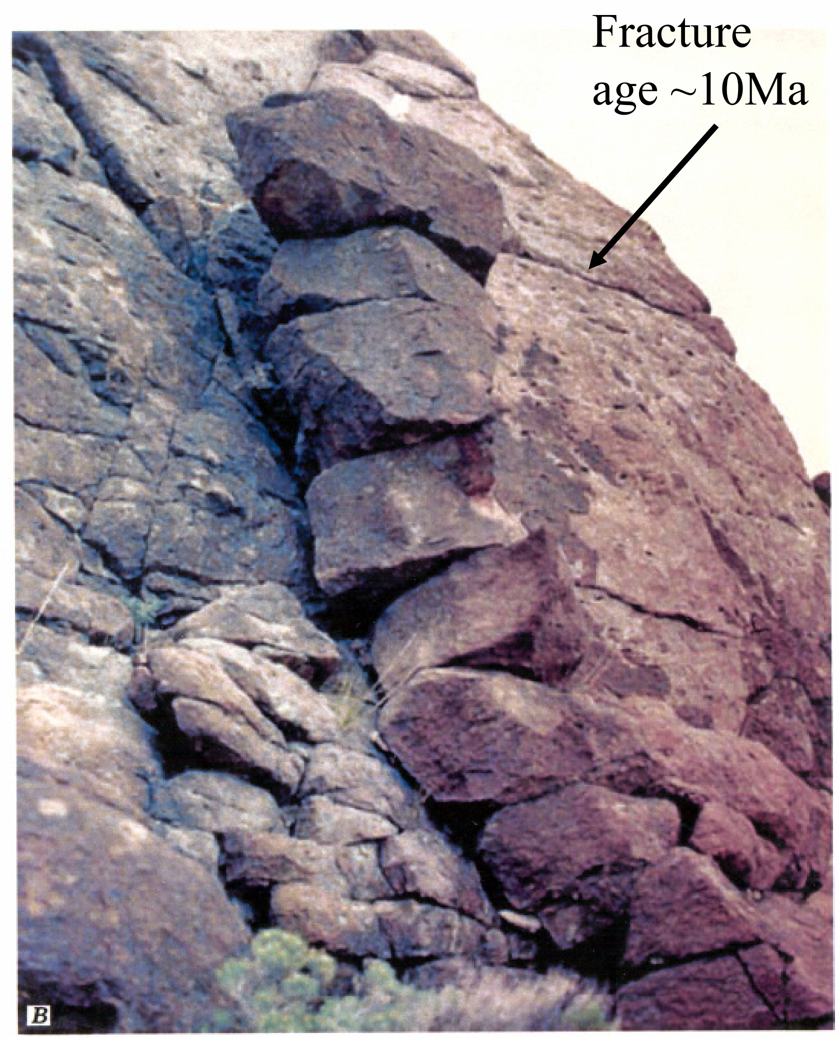
Mega-breccia from nuclear explosion-6g, 250 cm/s



Typical Cliff face At Yucca Mountain

Shattered rock, hanging wall, thrust fault, southern Calif.

Relatively intact rock, Yucca Mountain



$$\varepsilon = \frac{v}{\beta}$$

$$v = 1\,\text{m/s}$$

$$\beta = 500\,\text{m/s}$$

$$\varepsilon = 2 \times 10^{-3}$$

The extremes observed elsewhere are sufficient to drive a rock to fail, but that hasn't happened at Yucca Mtn.

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Low Amplitude Forcing

- 1999 Chi-Chi, Taiwan earthquake - “shake”

PGA =267 cm/sec^2

(209 cm/sec^2 threshold)

QuickTime™ and a
YUV420 codec decompressor
are needed to see this picture.

- 2002 Denali, Alaska earthquake - “push”

QuickTime™ and a
YUV420 codec decompressor
are needed to see this picture.

Higher Amplitude Forcing

- 1999 Chi-Chi, Taiwan earthquake - “shake”

PGA = 466 cm/sec^2

(209 cm/sec^2 threshold)

QuickTime™ and a
YUV420 codec decompressor
are needed to see this picture.

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Tentative Conclusions

- The hazard curves for Yucca Mountain significantly overestimate the hazard of extreme ground motions.
- The input used to generate those hazard curves must therefore be incorrect.
- Advanced computing will be needed to achieve significant improvements.

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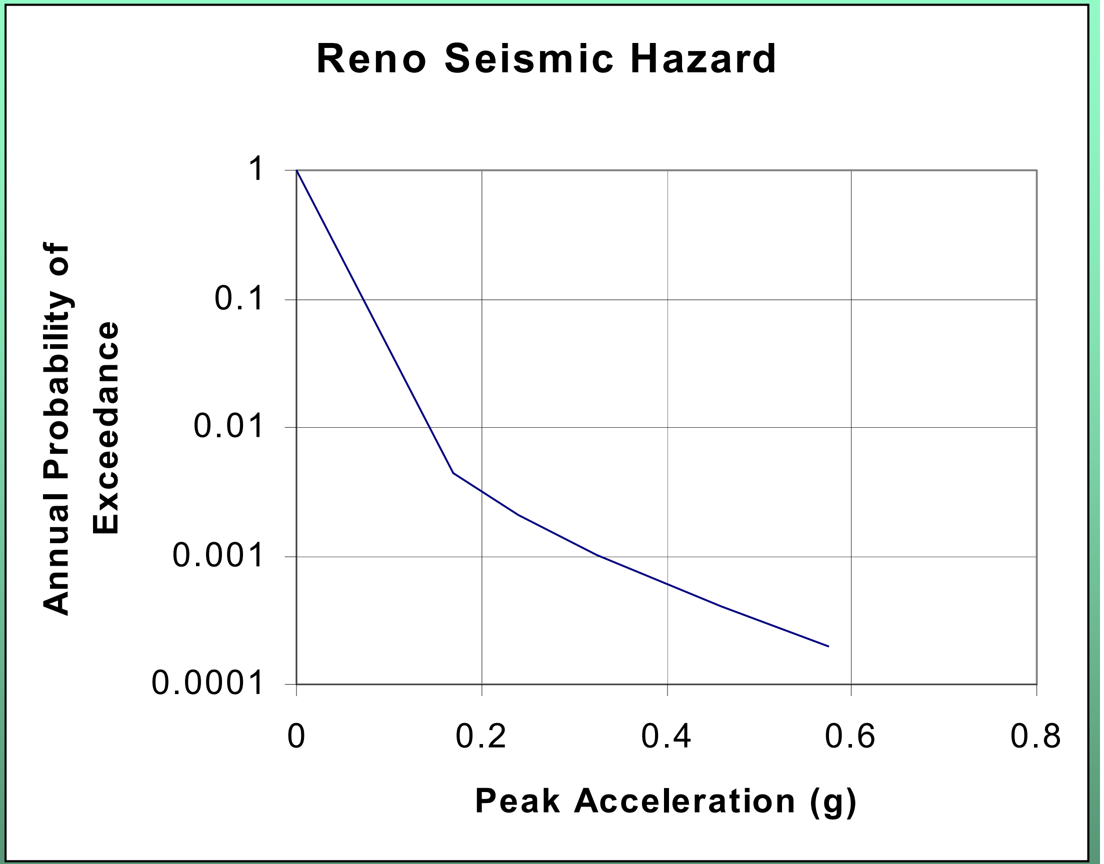
What is a Hazard Curve?

- Result of a physical experiment.
  - Run a strong-motion accelerograph at the site for 10^n years.
  - Measure how often a given peak acceleration is exceeded.



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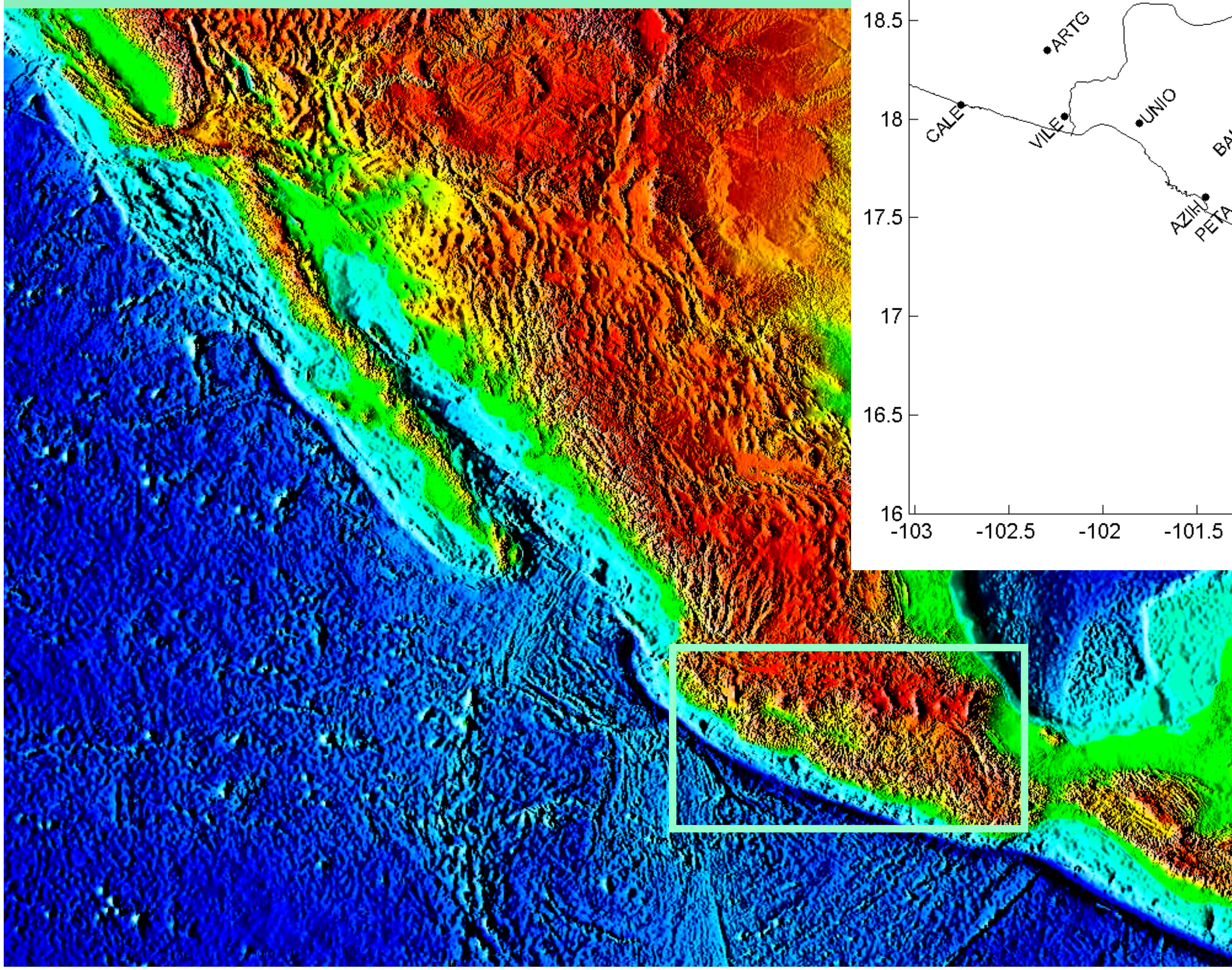
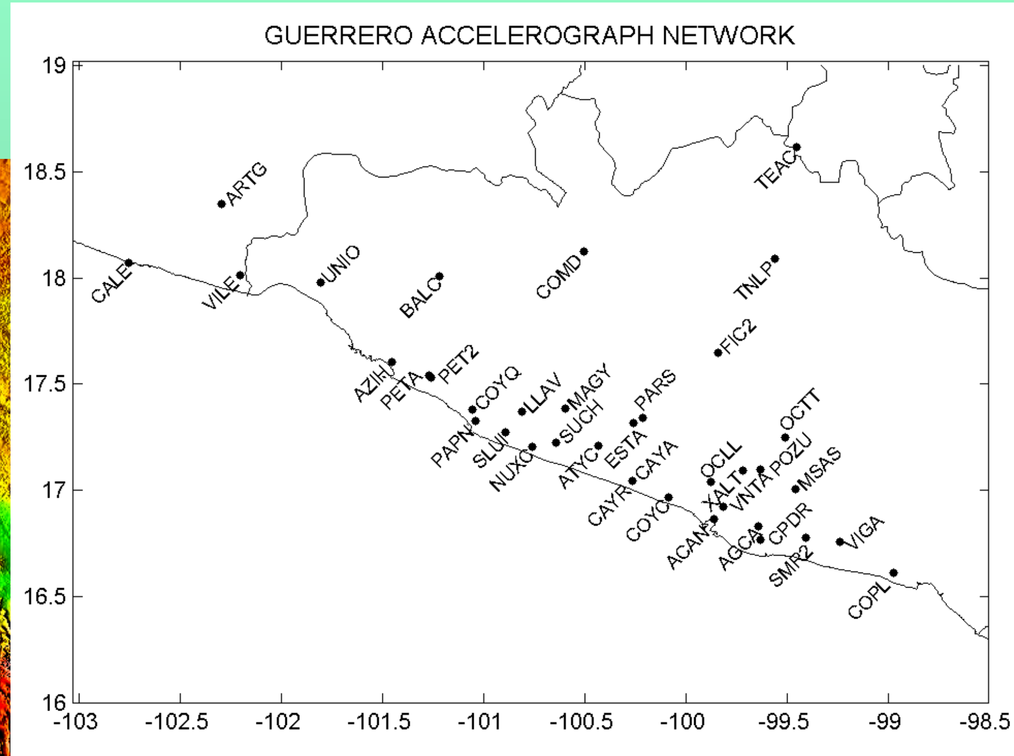
Guerrero Accelerograph Network





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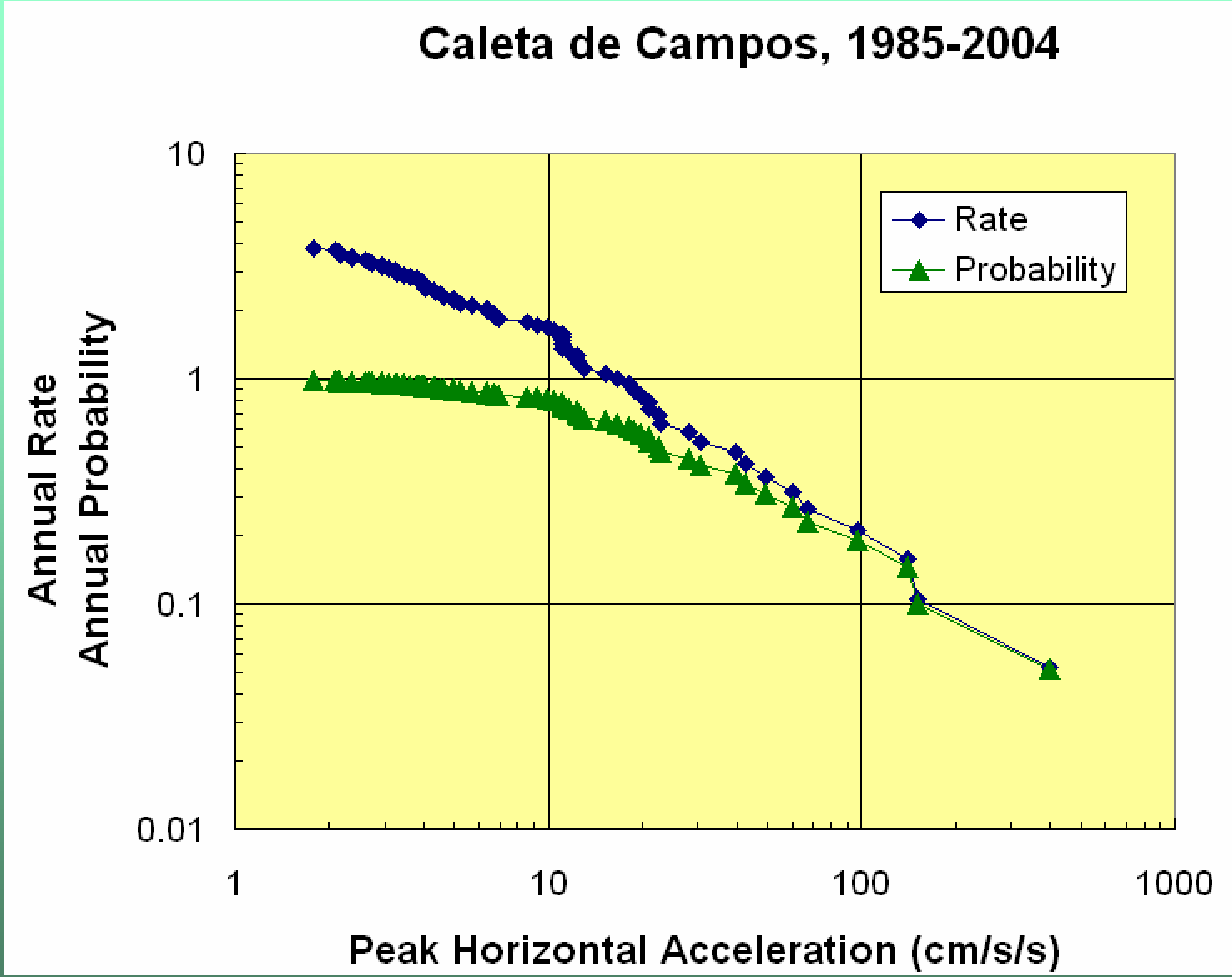

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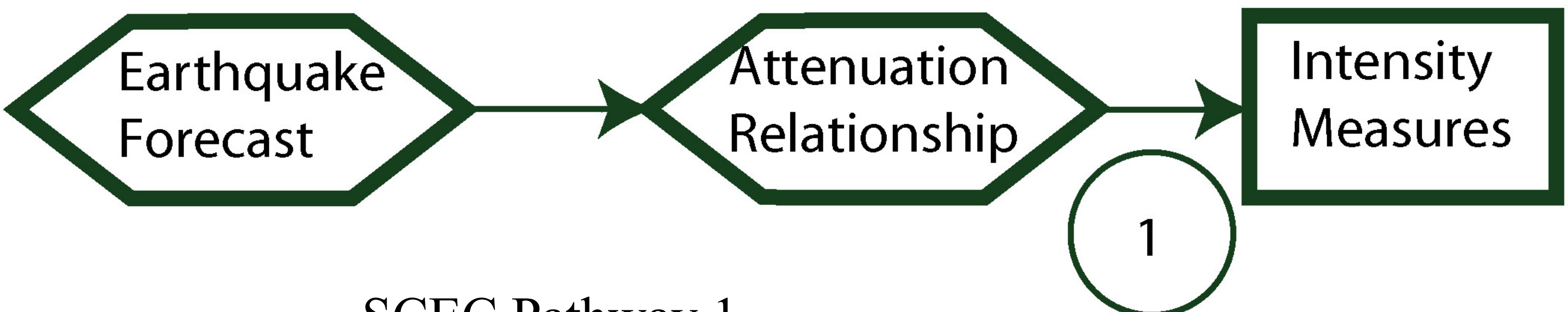
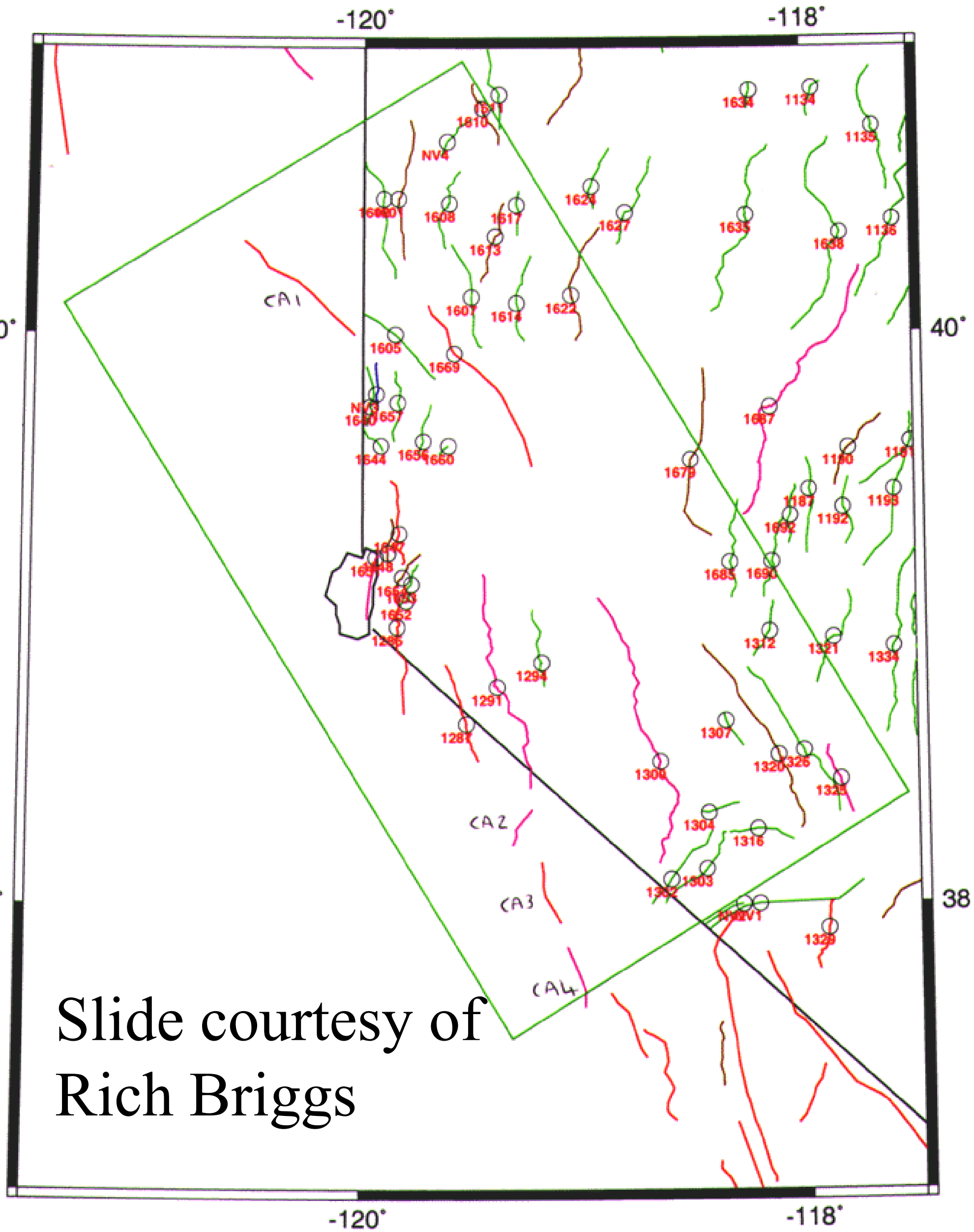
How a hazard curve is created

- Essentially follows the physical experiment.
- Create a model for the seismicity:
  - Distribution of earthquakes in space
  - Rate of occurrence for each earthquake.
- Create a model that predicts the ground motion from each earthquake.
- Combine this information in the mathematically correct way to estimate the hazard curve.



SCEC Pathway 1

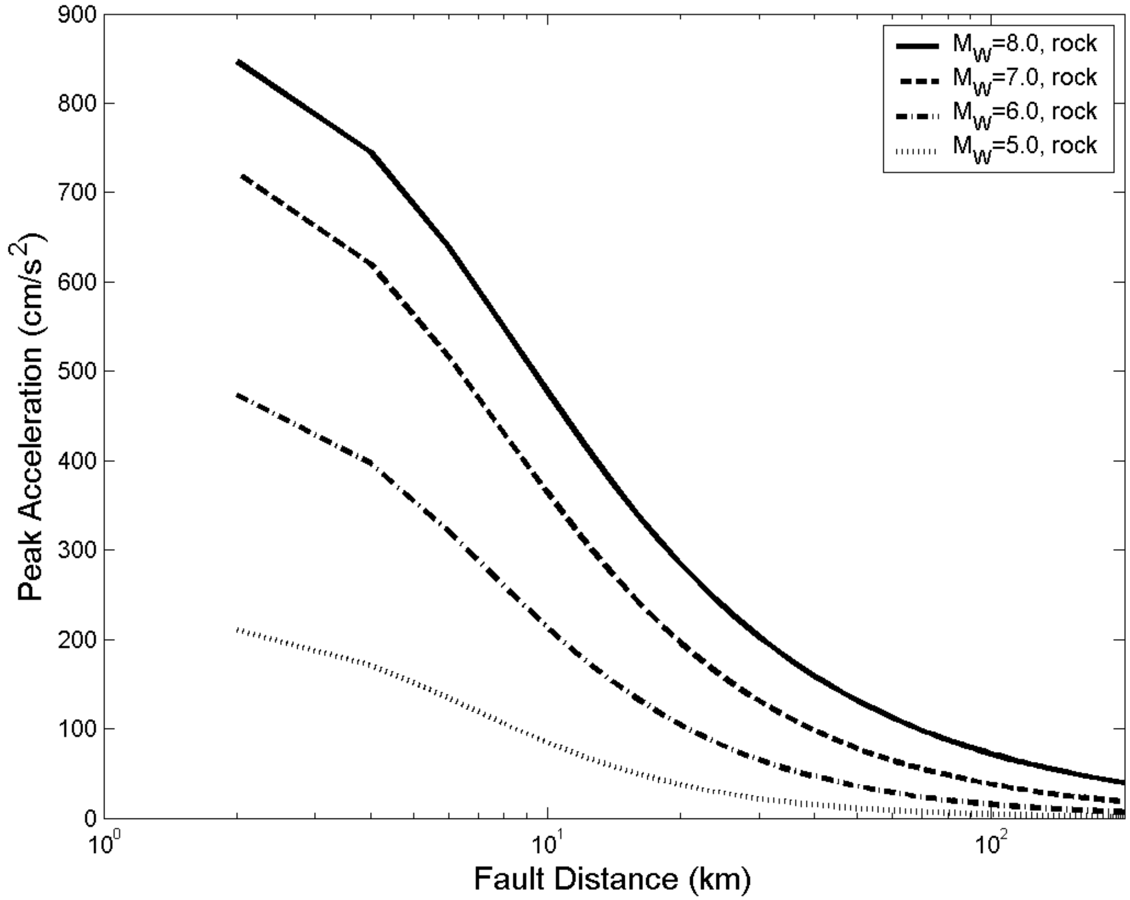
Source Model

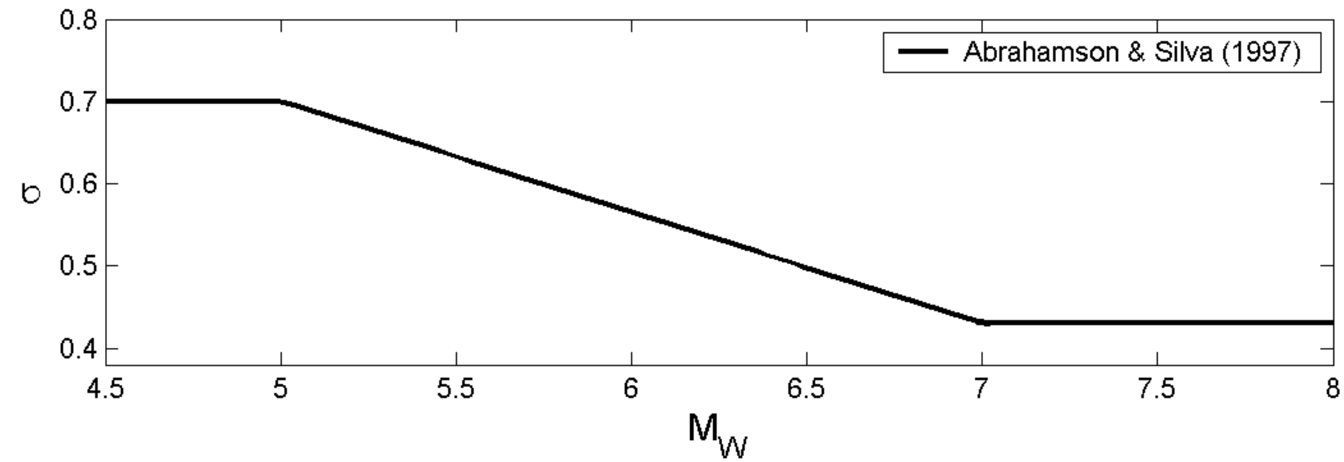


Slide courtesy of Rich Briggs

- Faults in USGS database of Quaternary faults

Ground Motion Prediction Equations (Attenuation Model) by Abrahamson and Silva, 1997





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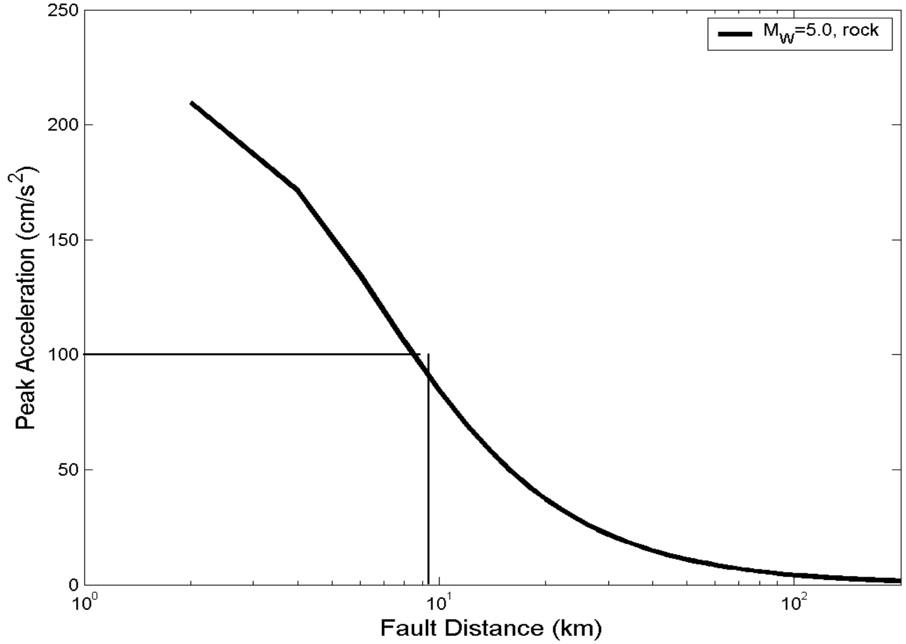
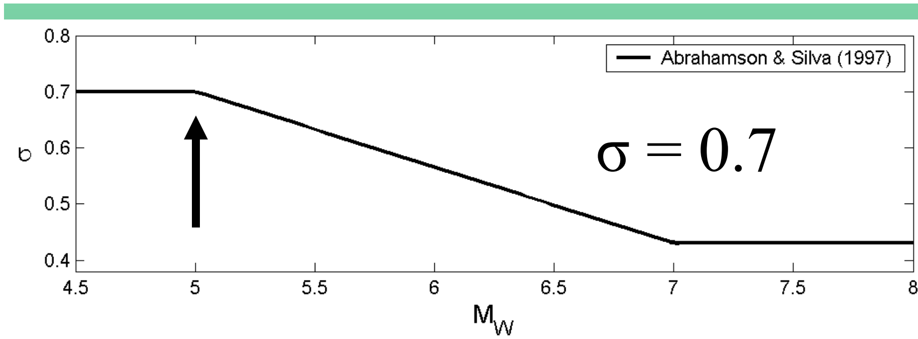
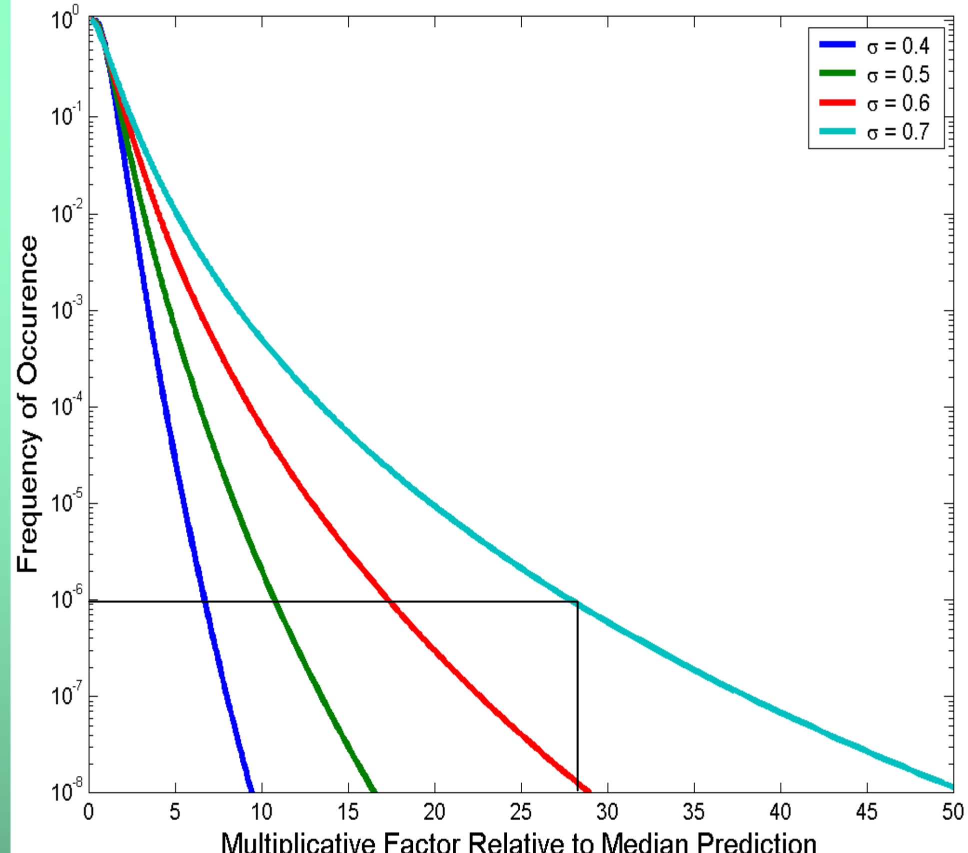
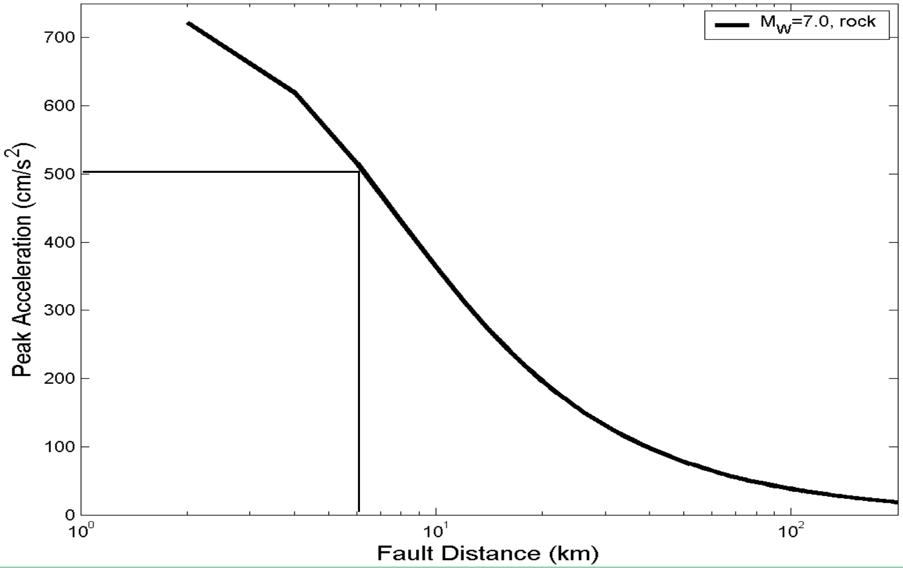


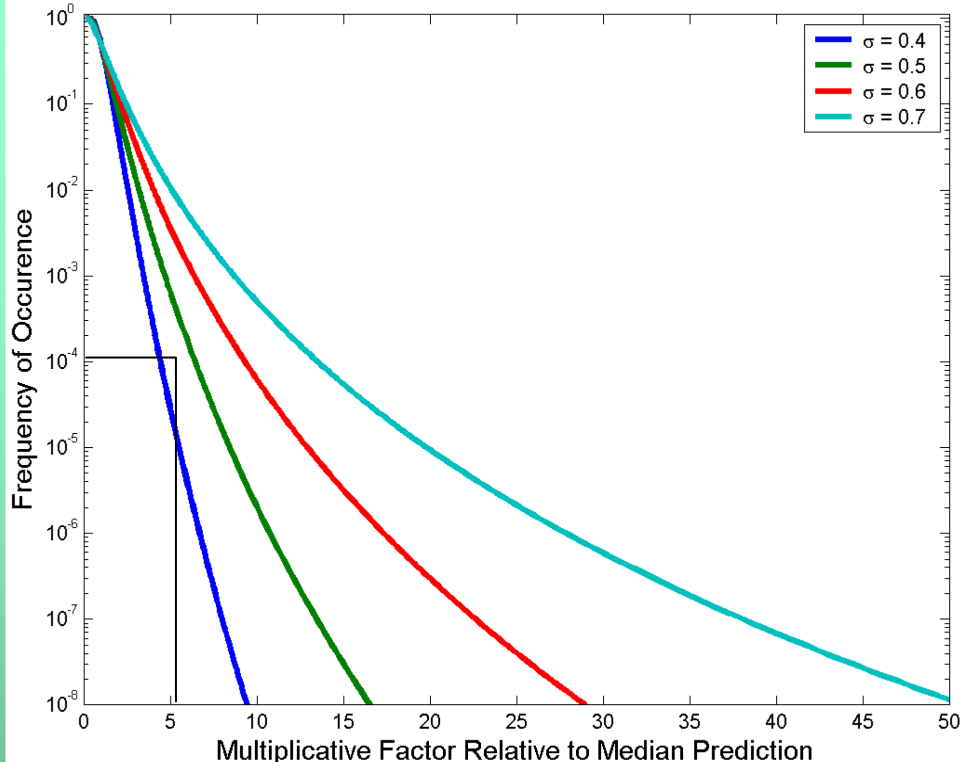


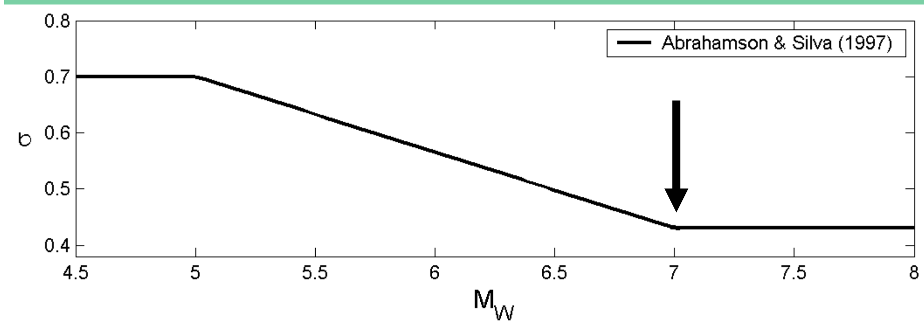


Consider an M=5 eq,
10 km, median ~100 cm/s^2
Rate 1/100 years

For $\sigma = 0.7$, once every 10^6 events, this peak acceleration is multiplied by a factor of 28,
so this model predicts 2.8g with a probability of 10^{-8}.







For $\sigma = 0.43$, once every 10^4 events, this peak acceleration is multiplied by a factor of 5.5, so this model predicts 2.8g with a probability of 10^{-8}.

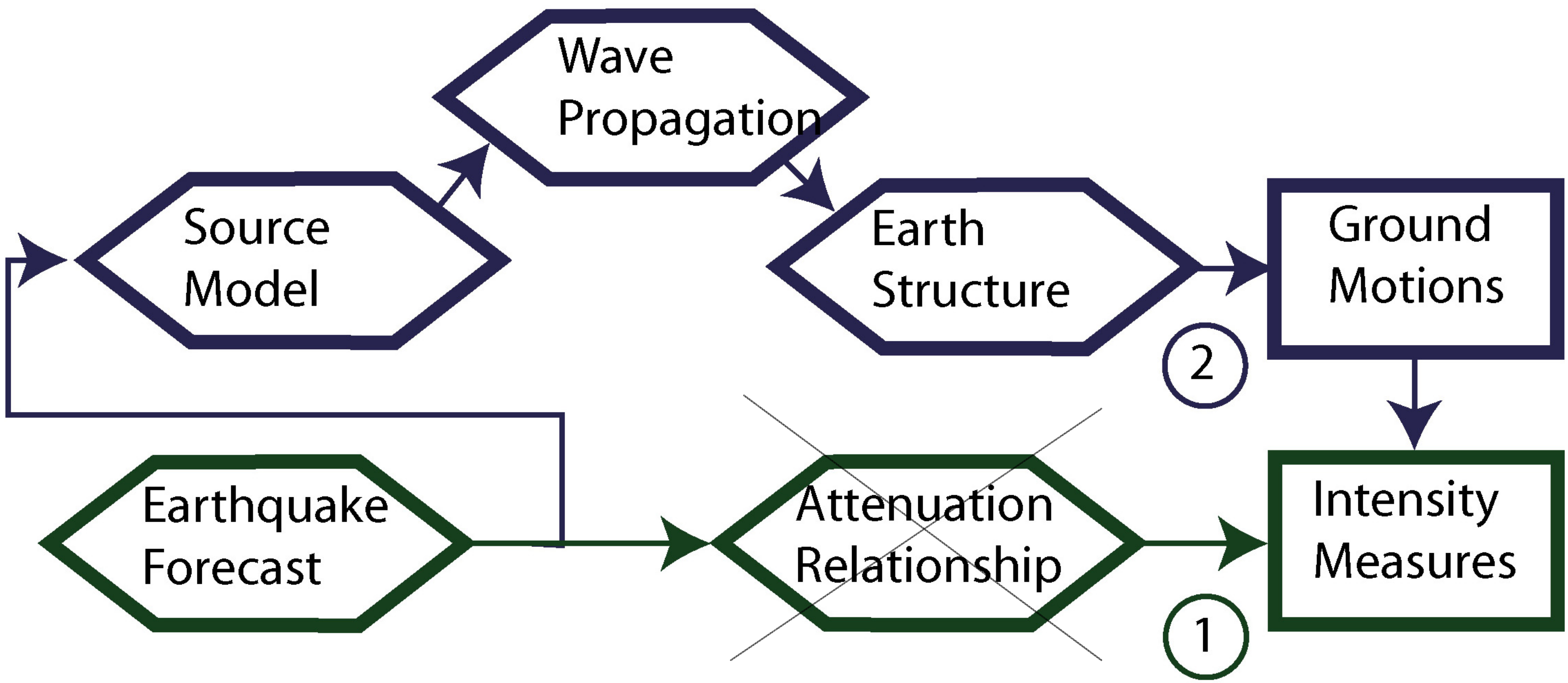
Consider an M=7 eq,
6 km, median ~500 cm/s^2
Rate 1/10,000 years

Comments

- The uncertainties are what drive the hazard up at low probabilities.
- Advanced simulations can reduce the uncertainties and give more realistic estimates of the seismic hazard.
- Goal: eventually ground motion prediction using physics of source and wave propagation will be much better than "attenuation" equations
- First, describe what the simulations would do, then why they will help.

SCEC "Pathway 2"

- Replaces the attenuation relationship with a **physics-based** simulation of the motions.



Representation Theorem

$$u_n(\vec{x},t) = \int_{-\infty}^{\infty} d\tau \iint_{\Sigma} \underline{\left[u_i\left(\vec{\xi},\tau\right)\right]} \, c_{ijpq} \nu_j \underline{\frac{\partial G_{np}\left(\vec{x},t-\tau;\vec{\xi},0\right)}{\partial \xi_q}} d\Sigma$$

Green's function

Elastic constants

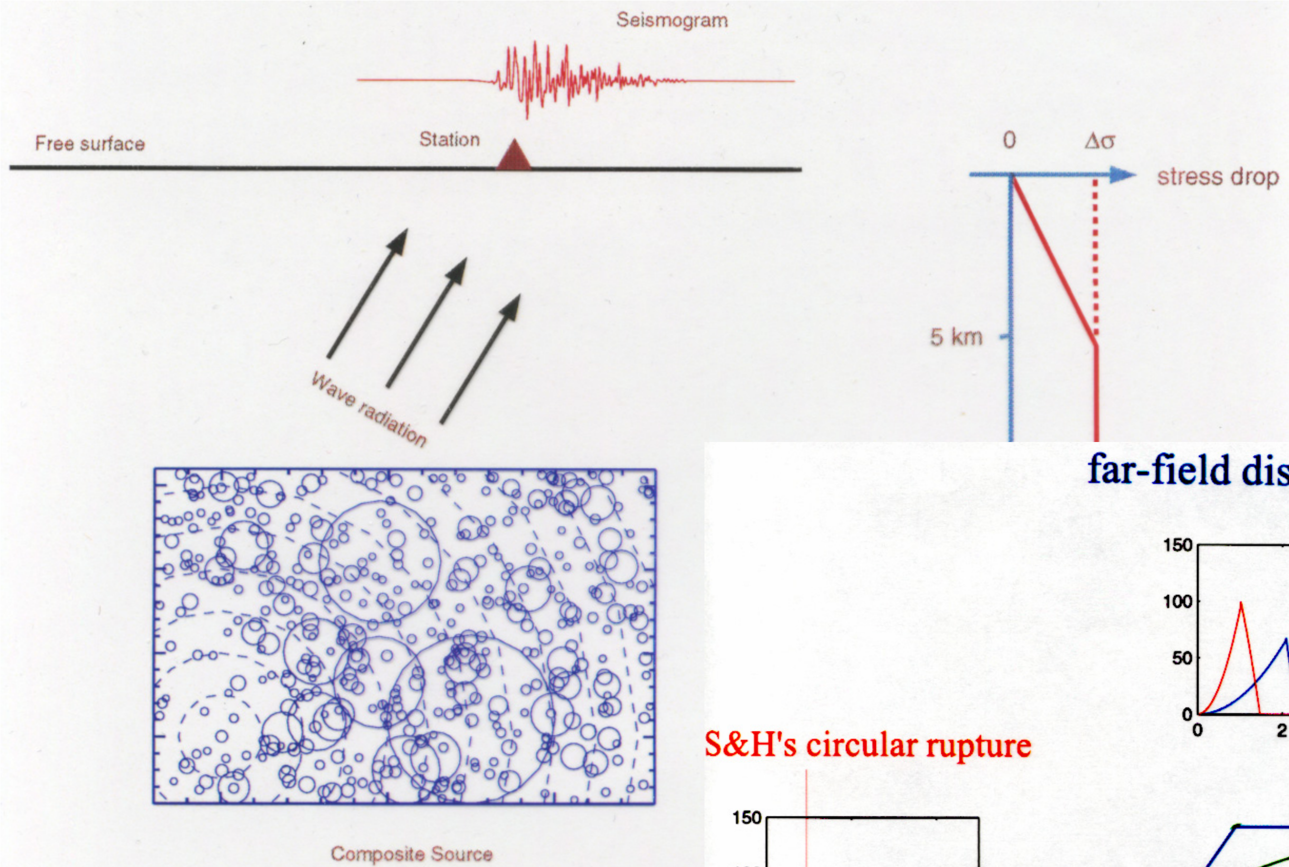
Slip on the fault

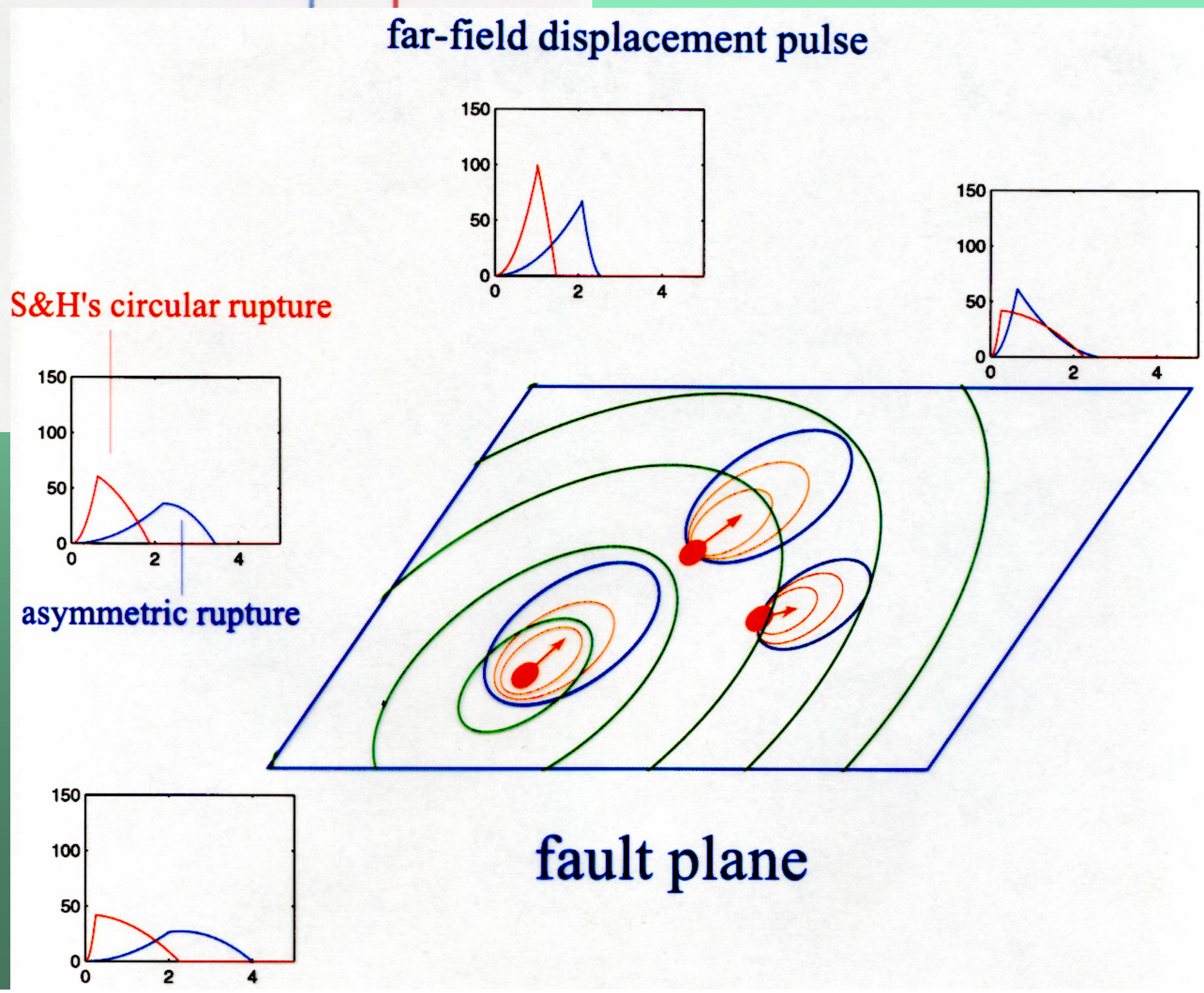
Integral over the fault surface

Convolution over time

Displacement at the station at location **x**

Composite Source Model

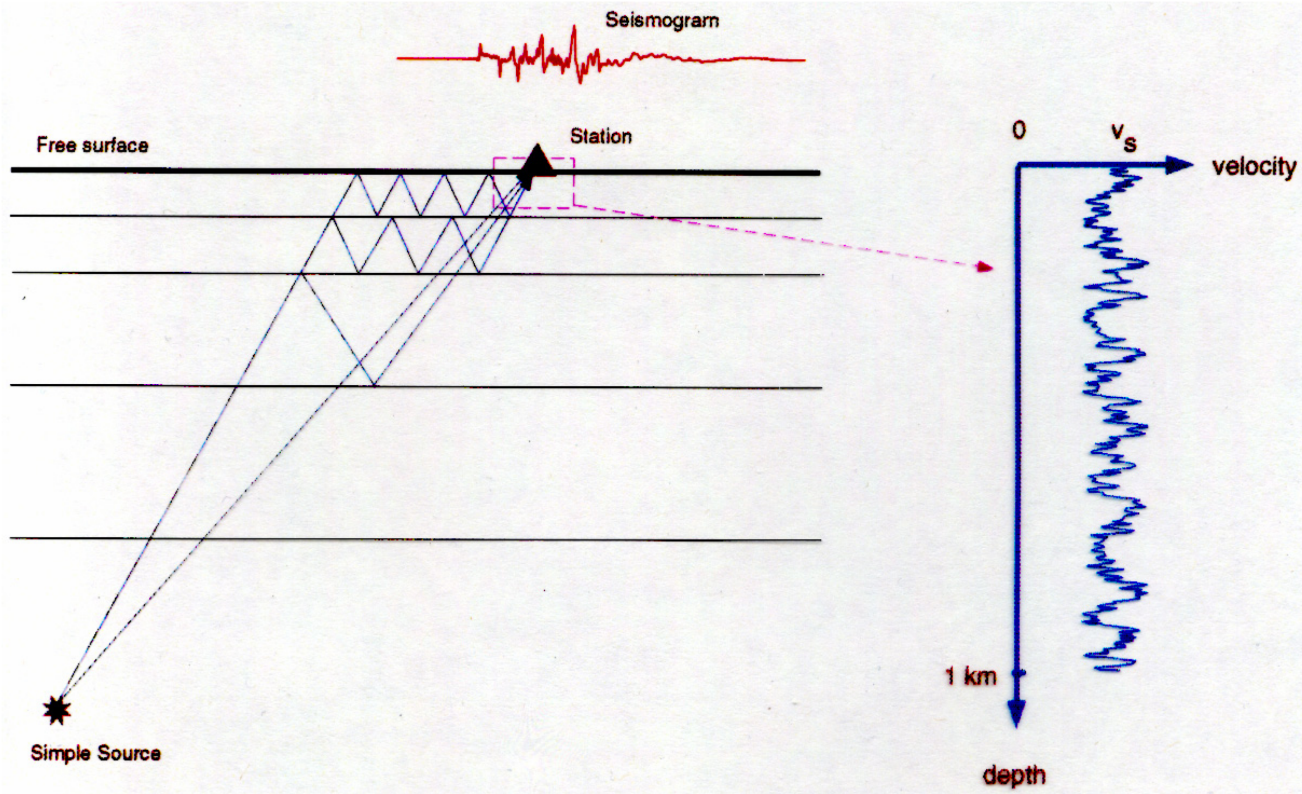


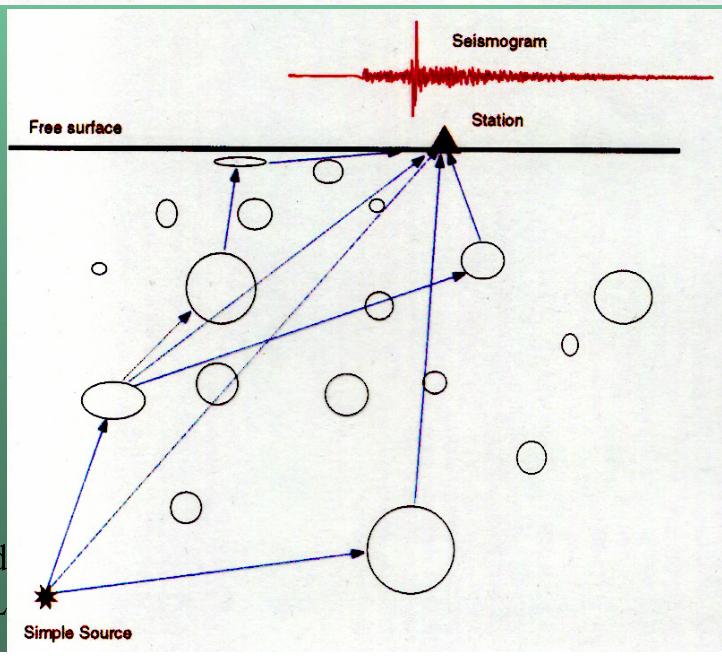


UNR approach
Yuehua Zeng
Yu Guang
John Anderson

Advanced Simulations
LLNL, December 14, 2005

Synthetic Green’s Functions





Ad
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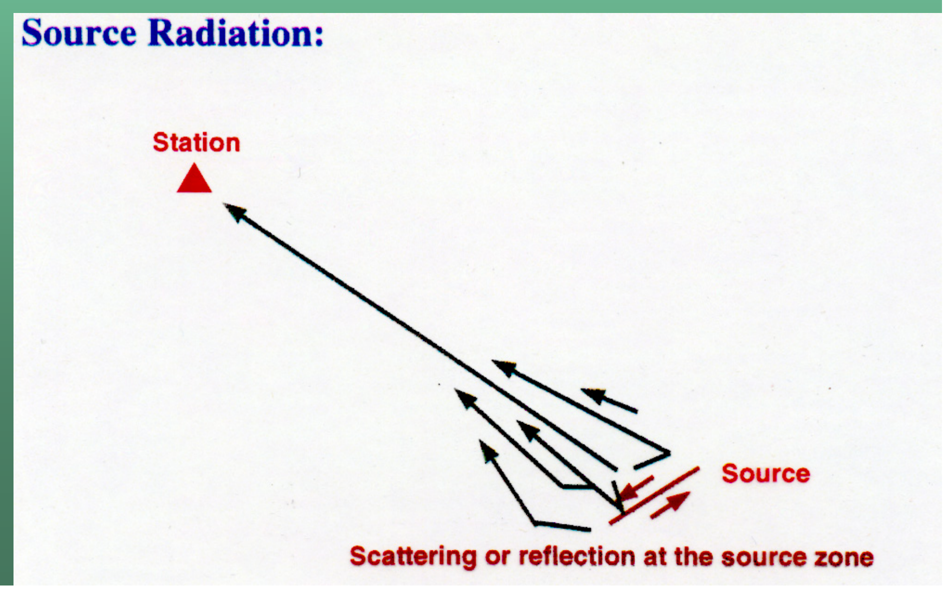


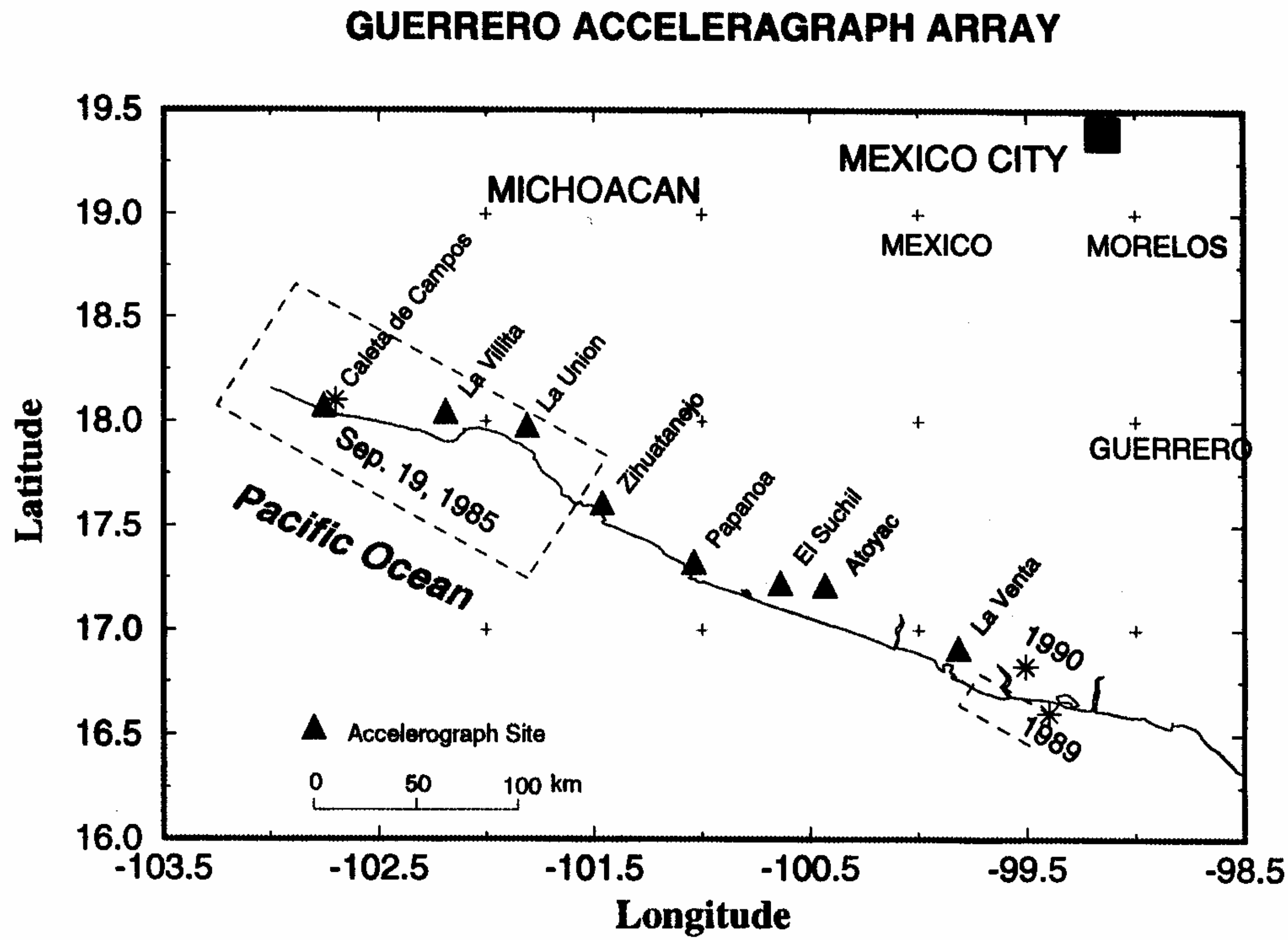
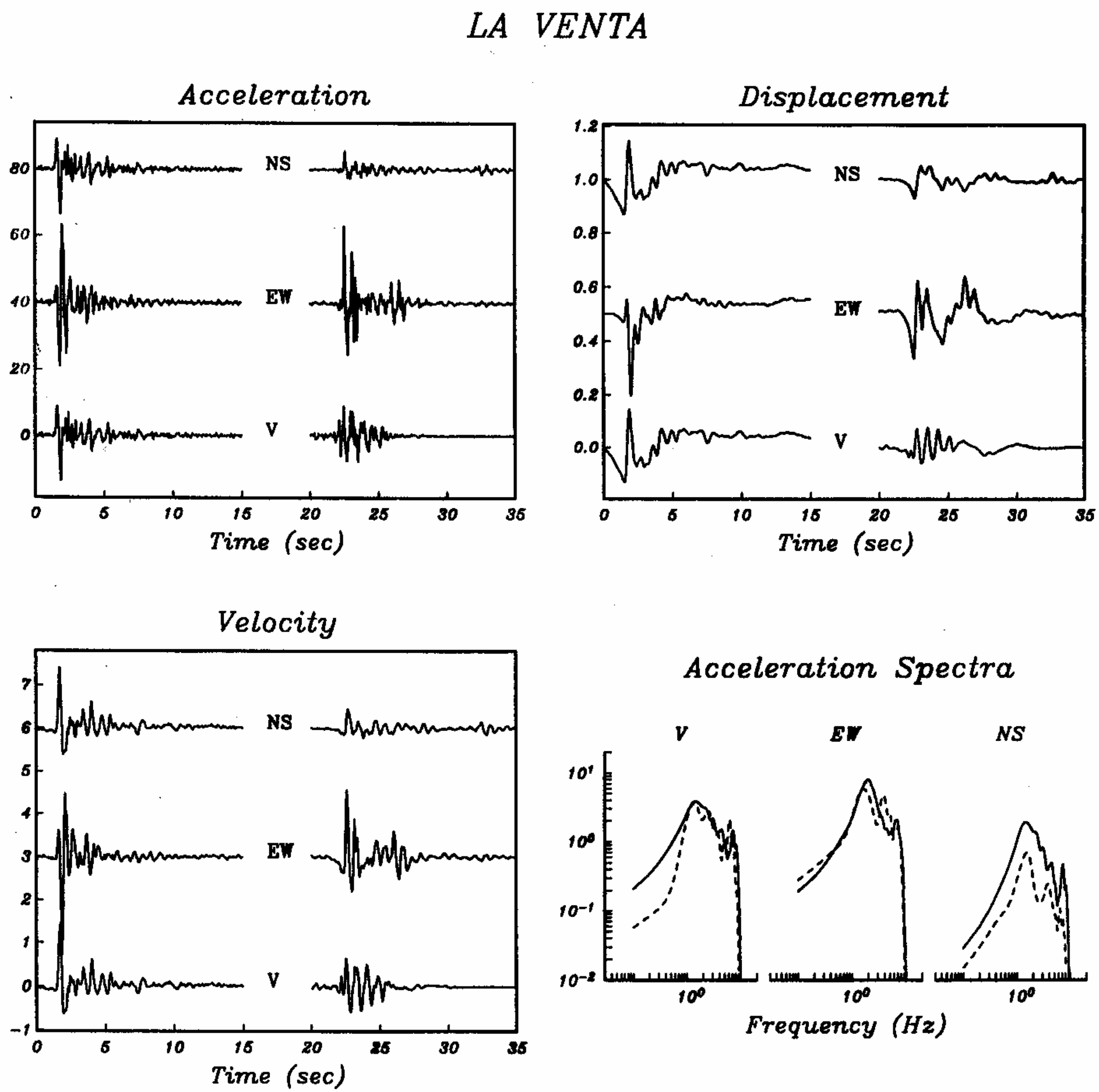
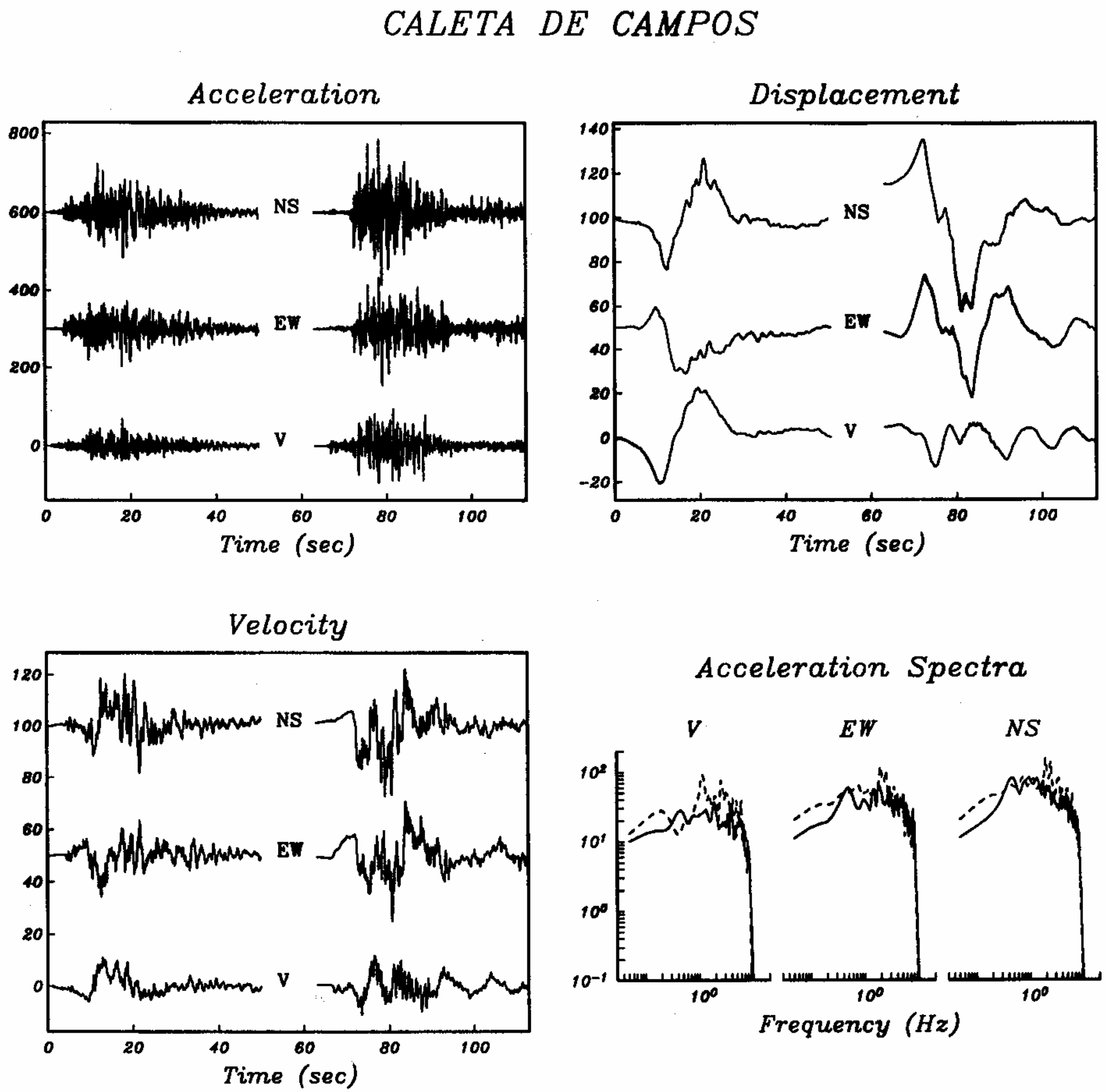


Figure 7. Epicenters, fault sizes, and station locations for the observed seismograms that are simulated in this study.



La Venta
Jan 13, 1990



Caleta de Campos
Sept 19, 1985

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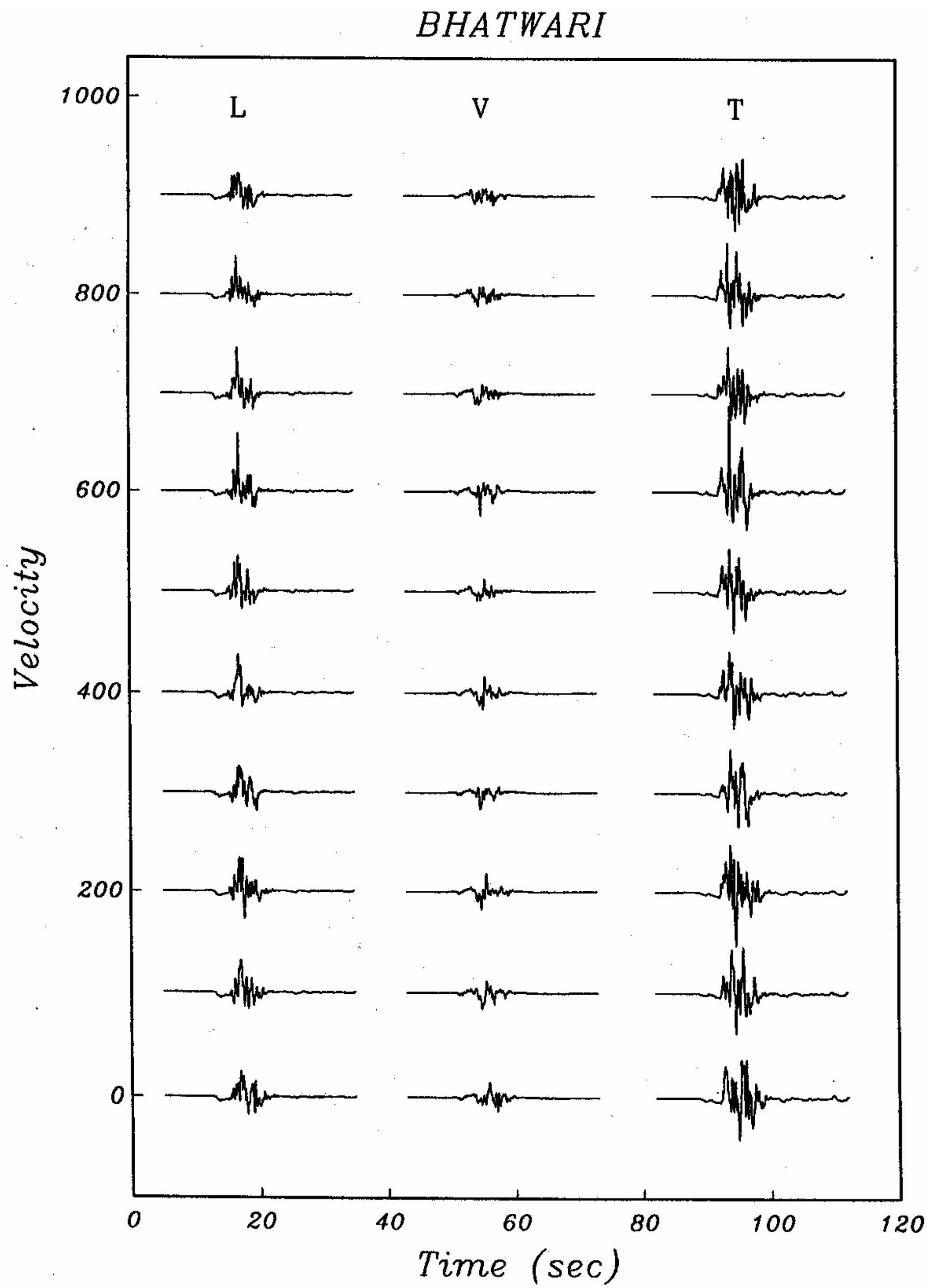
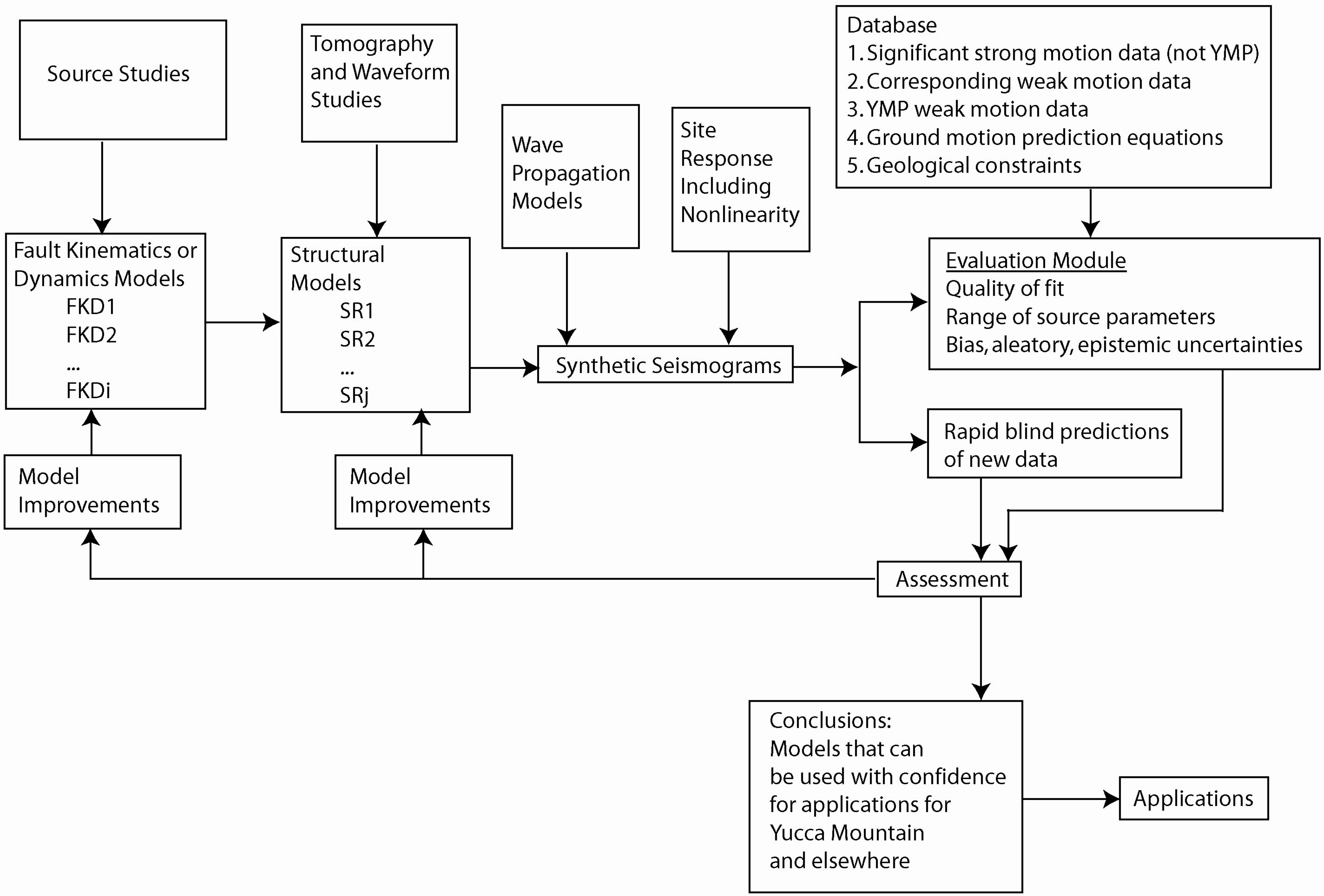
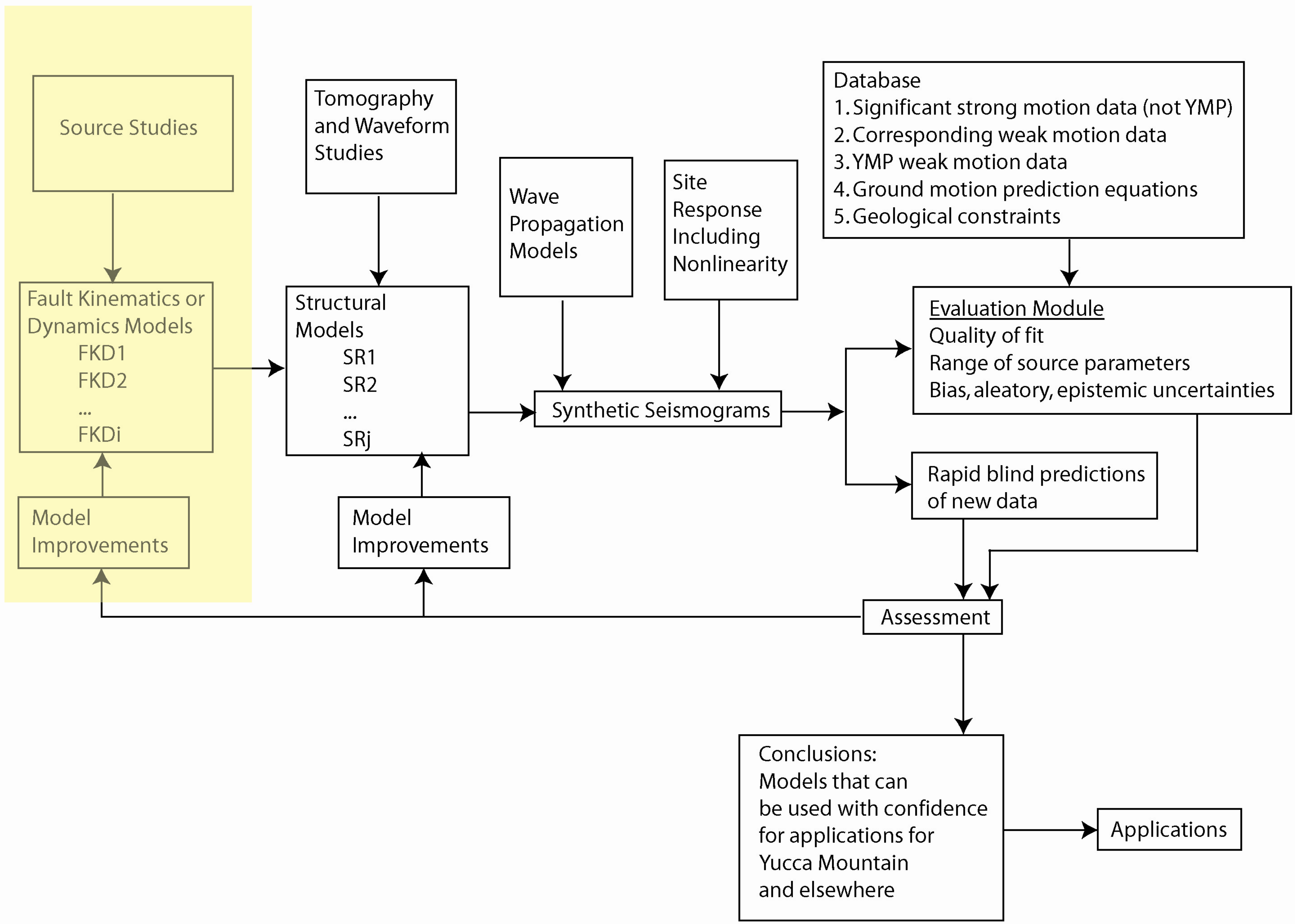


To use this (or any synthetic) method as a "ground motion prediction equation", you need to create multiple realizations of the seismograms, with different subevent locations, and then find the average parameters.

Proposal

- A computational system to use "Pathway 2" to carry out a probabilistic seismic hazard analysis.
  - Getting the physics right
  - Testing & calibrating new models
  - Convincing engineers that the method is reliable
  - Apply to the seismic hazard problem


Source Studies
Tomography and Waveform Studies
Wave Propagation Models
Site Response Including Nonlinearity
Database
1. Significant strong motion data (not YMP)
2. Corresponding weak motion data
3. YMP weak motion data
4. Ground motion prediction equations
5. Geological constraints
Fault Kinematics or Dynamics Models
FKD1
FKD2
...
FKDi
Structural Models
SR1
SR2
...
SRj
Synthetic Seismograms
Evaluation Module
Quality of fit
Range of source parameters
Bias, aleatory, epistemic uncertainties
Rapid blind predictions of new data
Model Improvements
Model Improvements
Assessment
Conclusions:
Models that can be used with confidence for applications for Yucca Mountain and elsewhere
Applications



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PFC2D 3.10

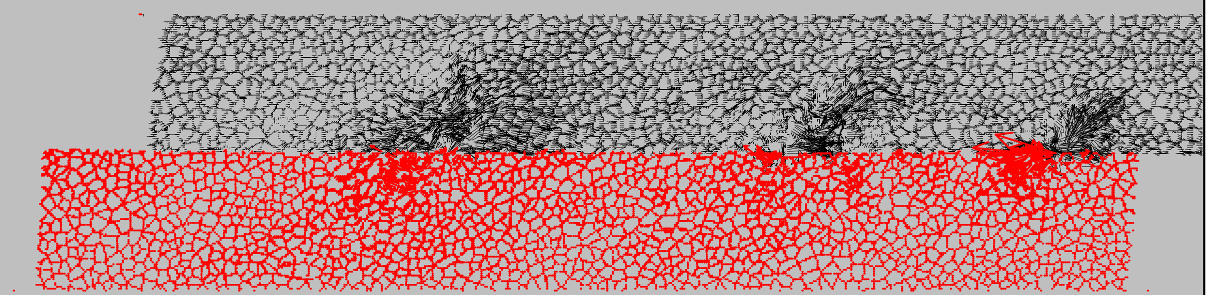
Step 303060 20:52:51 Fri Sep 02 2005

View Size:
X: -5.200e-003 <=> 1.092e-001
Y: -5.130e-002 <=> 8.065e-002

Velocity
Maximum = 3.591e-002
Linestyle

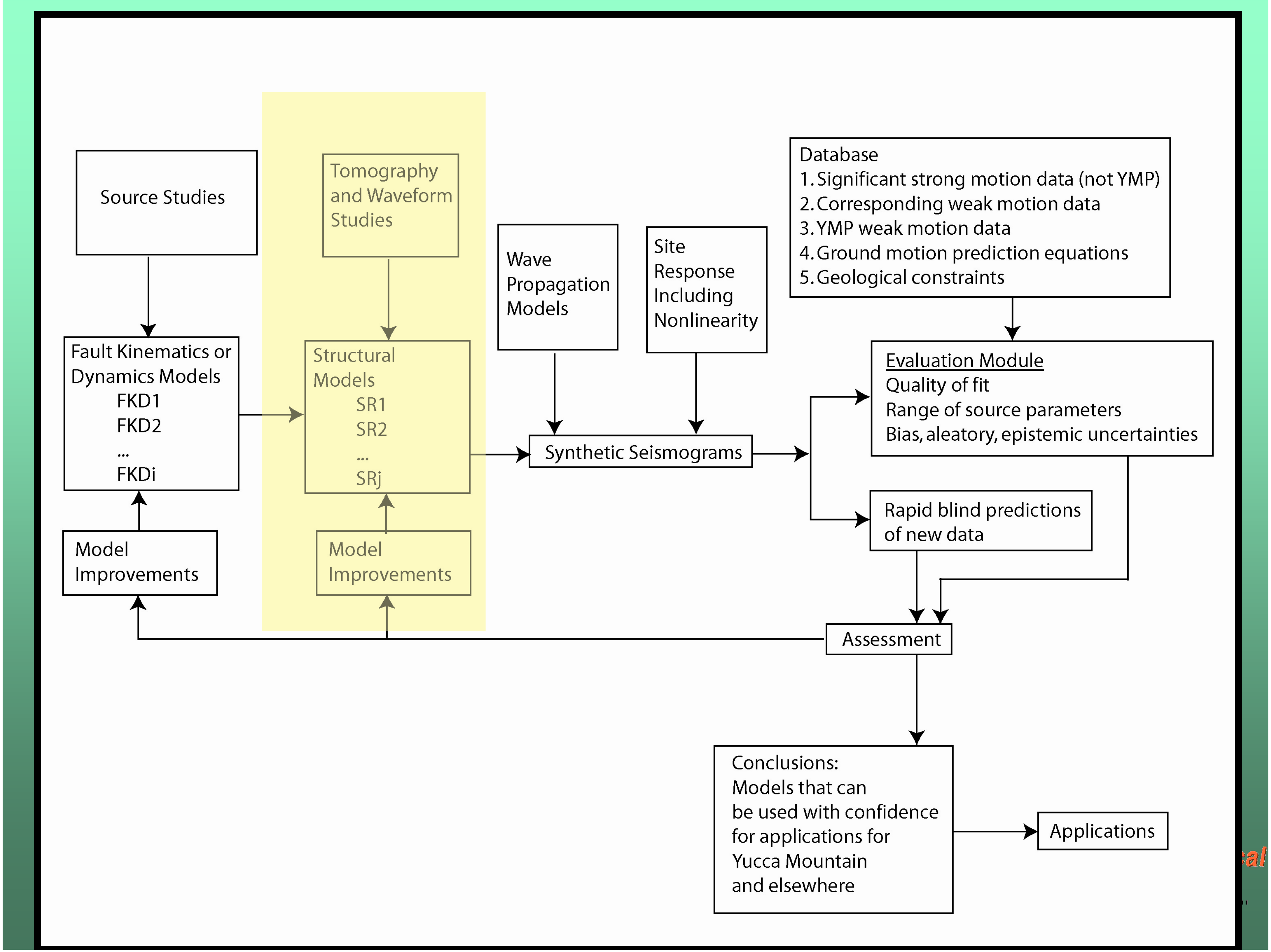
Velocity
Maximum = 6.415e-002
Linestyle

Matthew Purvance



Source Models

- Composite source model is one of many.
  - Kinematic: Somerville, Archuleta, Irikura, …
  - Dynamic: Olsen, Day, Purvance, …
- It's relatively easy to come up with a broadband source model, but there is no easy way to test it thoroughly.
  - Developing an easy mechanism to test source models would be a huge benefit to engineering seismology.



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Earth Structure Models

- State of the art is to develop tomographic models for the region.
- Grand challenge: adjust structure model to improve fit to complete seismogram, without sacrificing the fit to older data.

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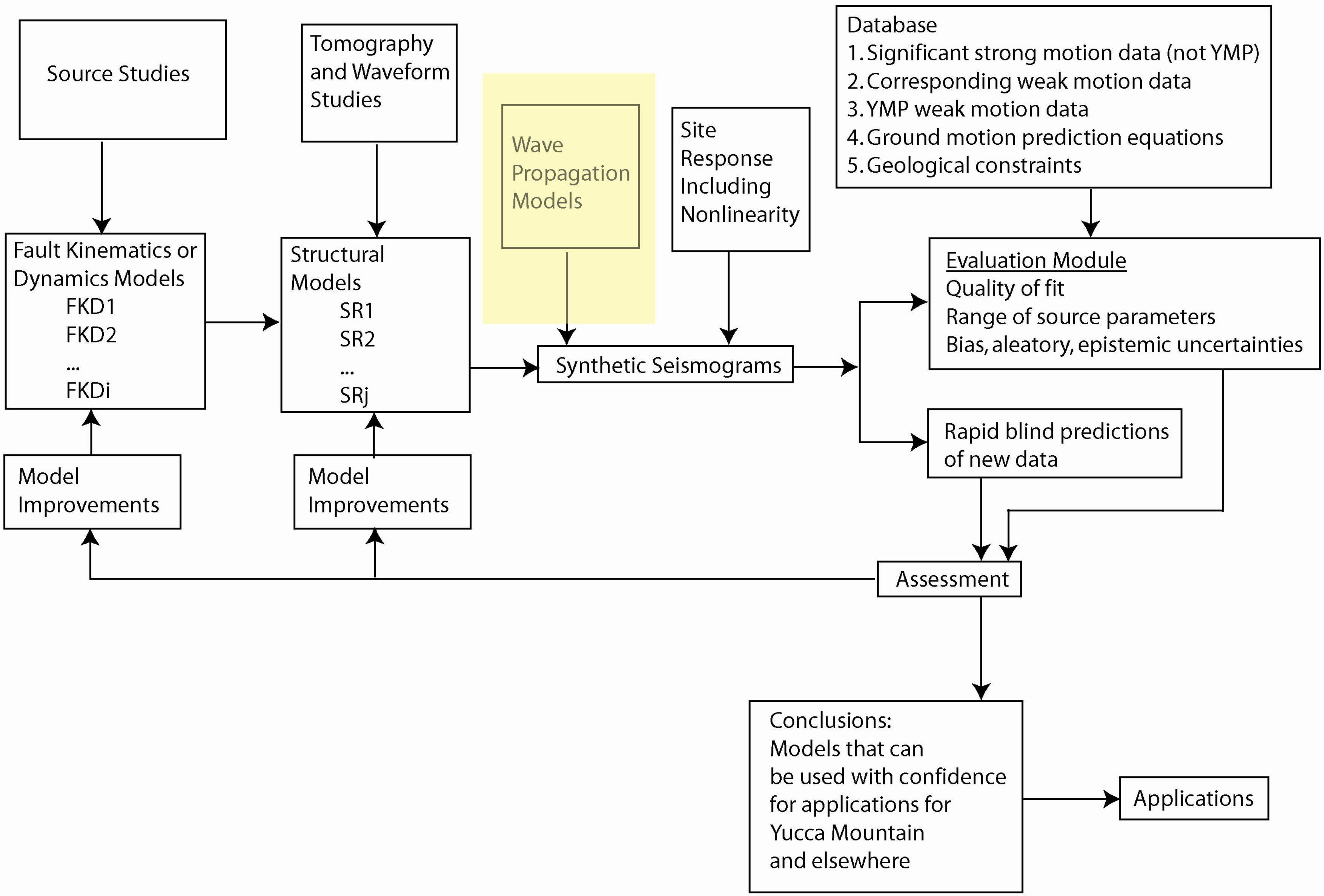

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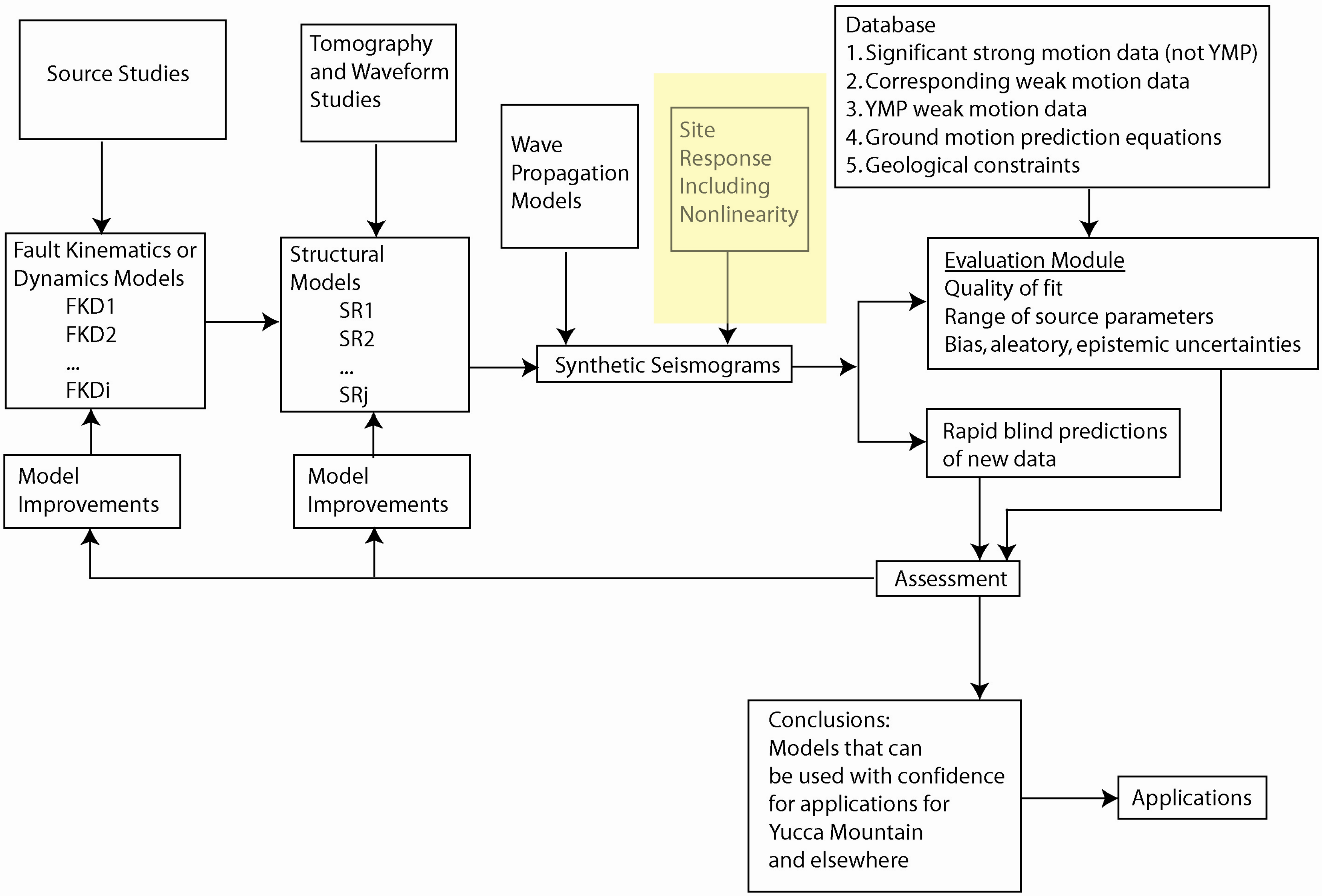
Wave Propagation Models

- 3D Earth structure. Also need attenuation, topography.
- Usually now use finite difference or finite elements. Currently ~1 Hz.
- Challenge: push those models to higher frequency. Engineering seismology needs up to 20 Hz.



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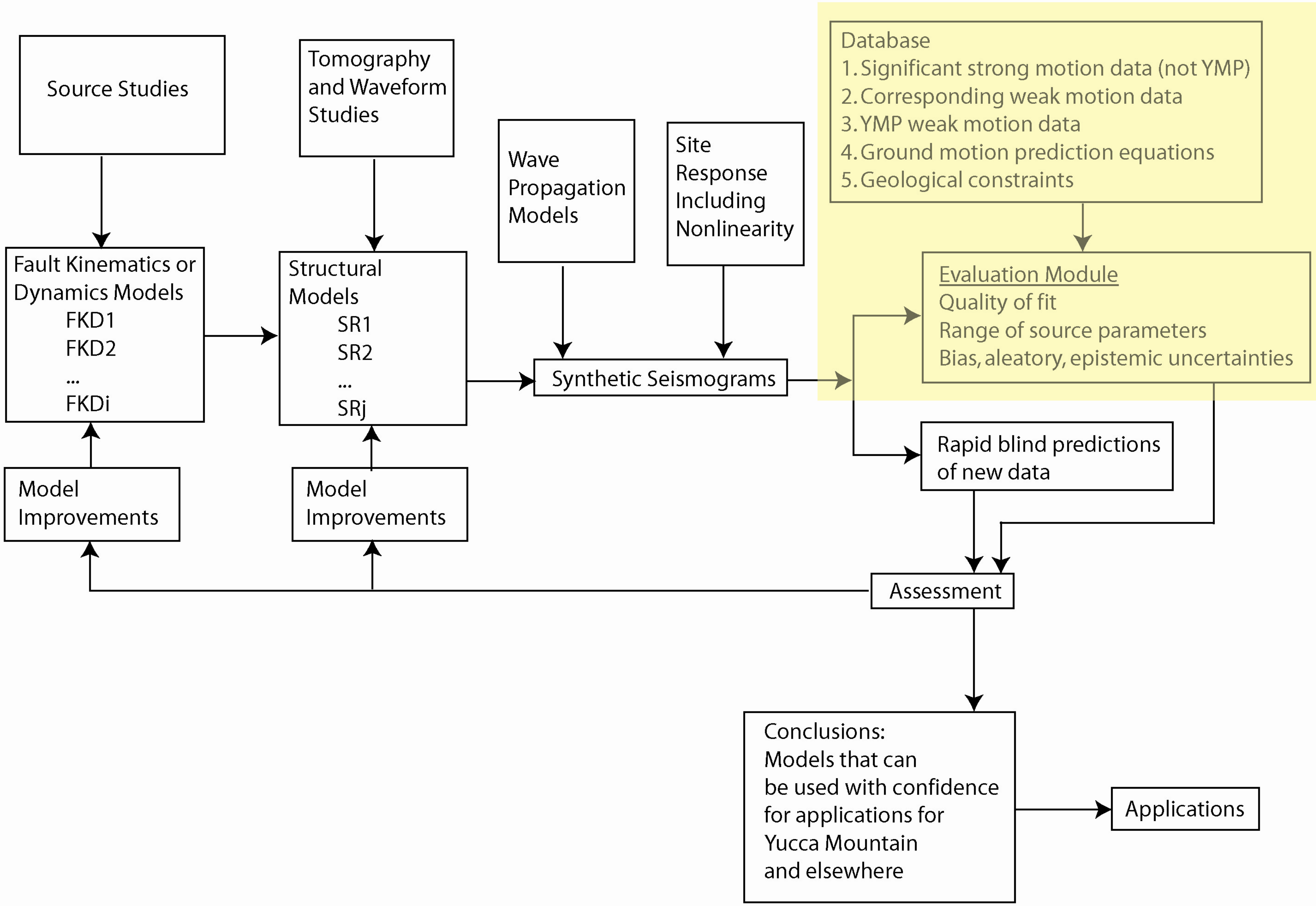
Effects of Surface Geology

- Requires detailed investigation of the near-surface.
- Nonlinear stress-strain curves.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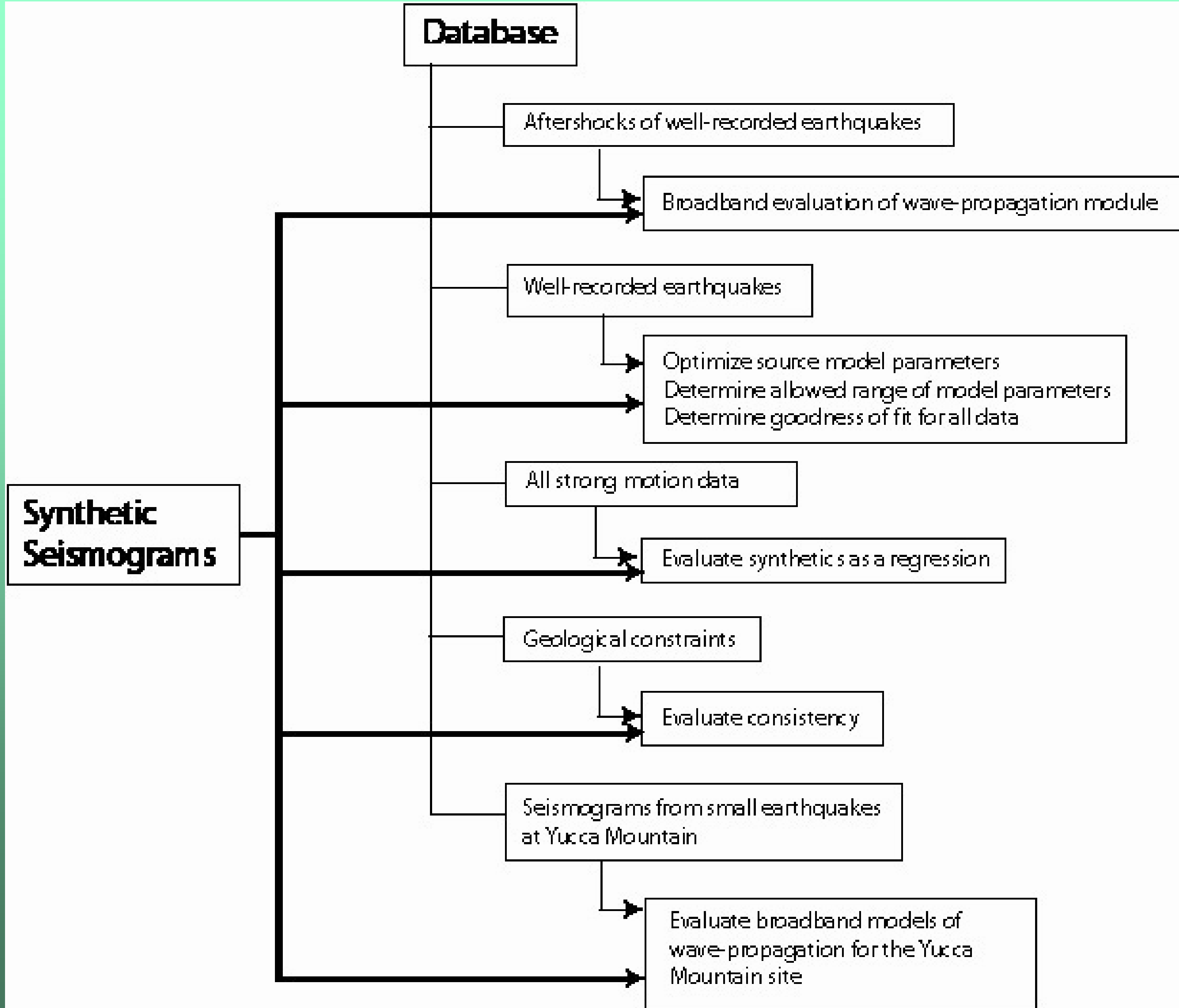
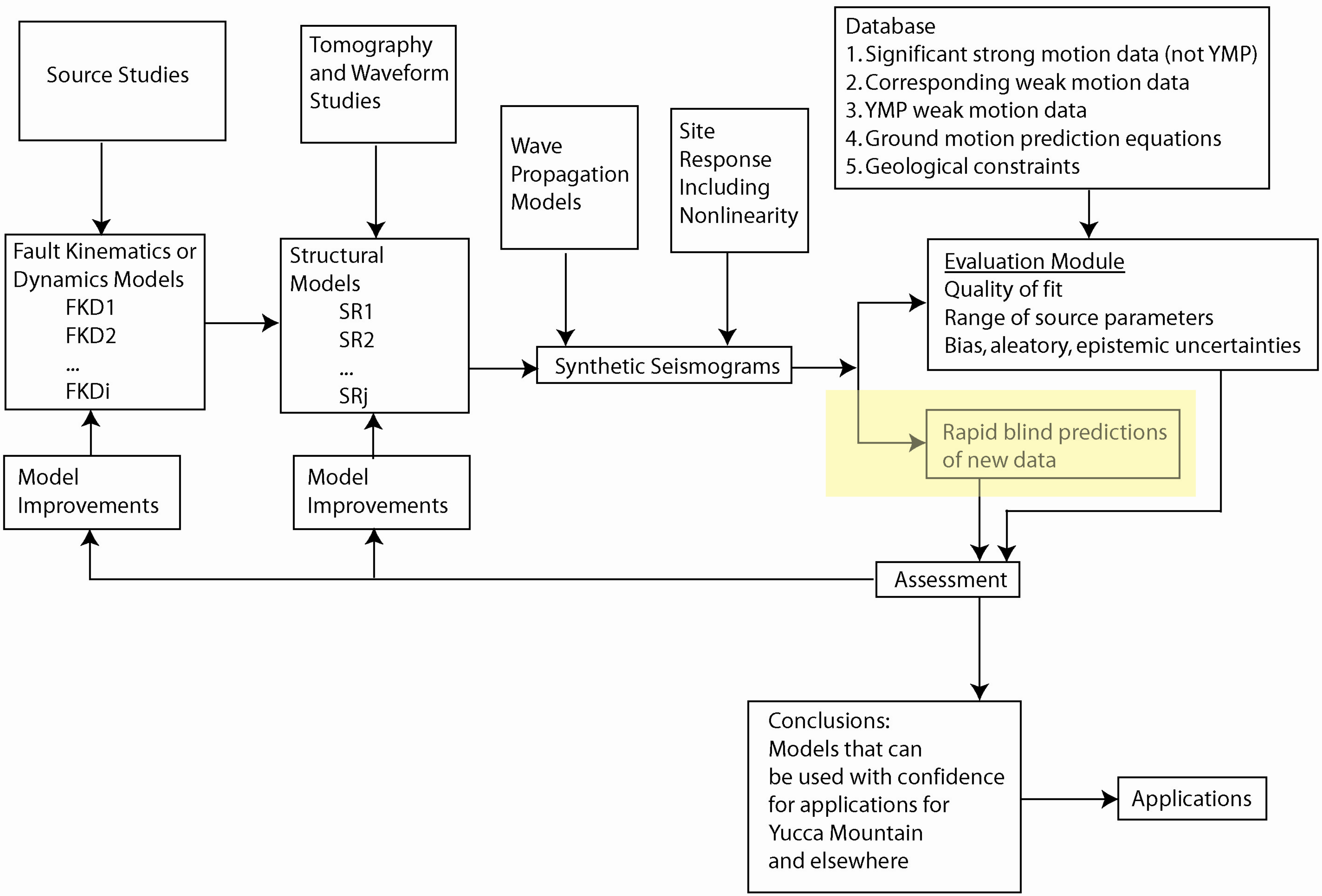

Database
Aftershocks of well-recorded earthquakes
Broadband evaluation of wave-propagation module
Well-recorded earthquakes
Optimize source model parameters
Determine allowed range of model parameters
Determine goodness of fit for all data
All strong motion data
Evaluate synthetics as a regression
Geological constraints
Evaluate consistency
Seismograms from small earthquakes at Yucca Mountain
Evaluate broadband models of wave-propagation for the Yucca Mountain site
Synthetic Seismograms

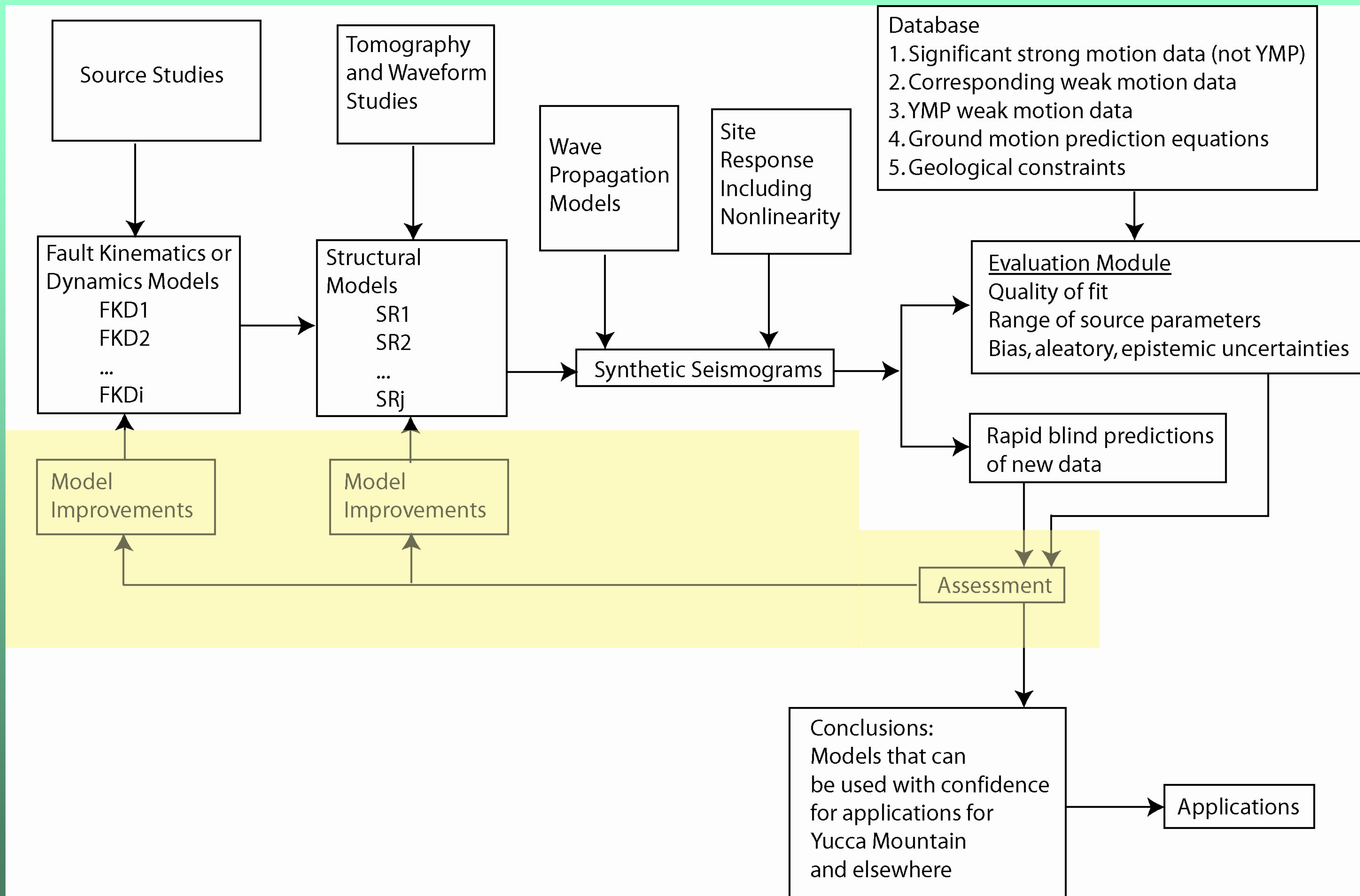
Testing and Improving Synthetics

- Need a way to score the quality of the synthetics.
- Appropriate database to test all the components of the system
- Select parameters to minimize bias, maximize quality of fit for many parameters
- Requires sophisticated system to carry out rapid evaluations of multiple models.


Source Studies
Tomography and Waveform Studies
Wave Propagation Models
Site Response Including Nonlinearity
Database
1. Significant strong motion data (not YMP)
2. Corresponding weak motion data
3. YMP weak motion data
4. Ground motion prediction equations
5. Geological constraints
Fault Kinematics or Dynamics Models
FKD1
FKD2
...
FKDi
Structural Models
SR1
SR2
...
SRj
Synthetic Seismograms
Evaluation Module
Quality of fit
Range of source parameters
Bias, aleatory, epistemic uncertainties
Rapid blind predictions of new data
Model Improvements
Model Improvements
Assessment
Conclusions:
Models that can be used with confidence for applications for Yucca Mountain and elsewhere
Applications

Credibility of Synthetics

- Credibility through "blind predictions".
  - As soon as an earthquake occurs
  - Open software
  - Tested by a neutral party rather than by the advocates.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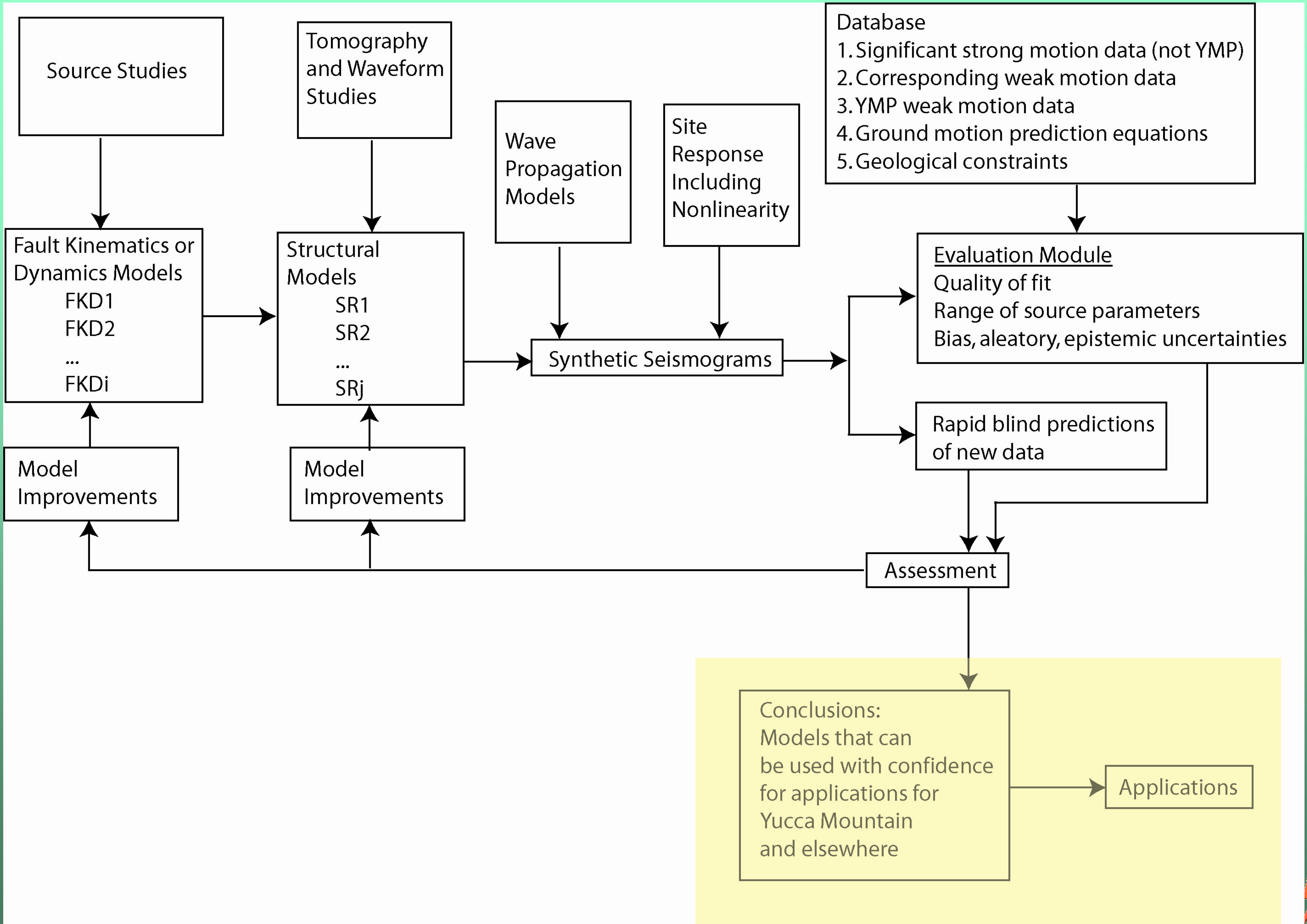
Feedback Loop

- Ability to improve models to achieve a better fit to the data.
- Adjust model parameters.
- Improve velocity model.
- Improves nonlinear stress-strain models for near-surface geological effects
- Improve computational system – larger models, higher frequencies.



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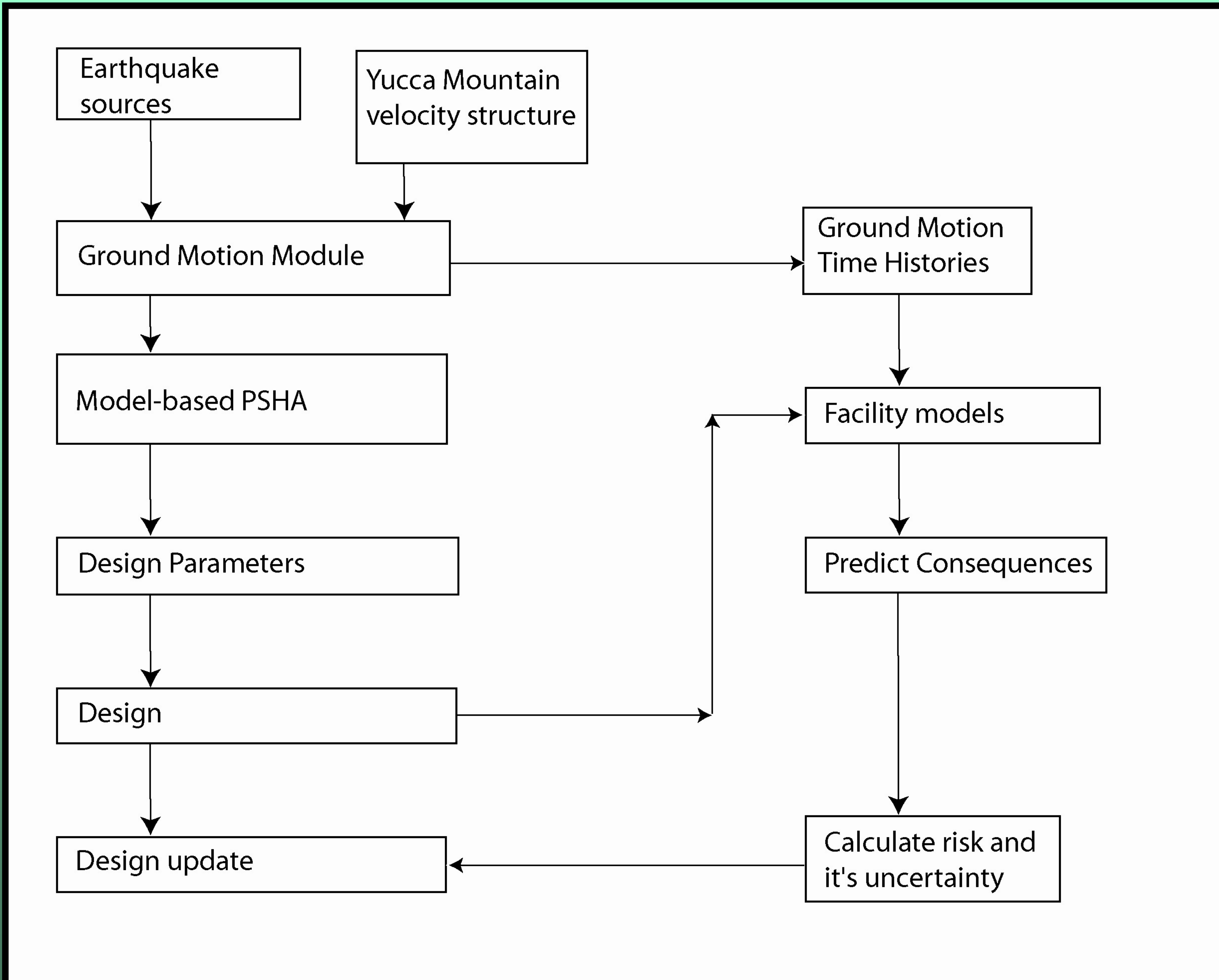
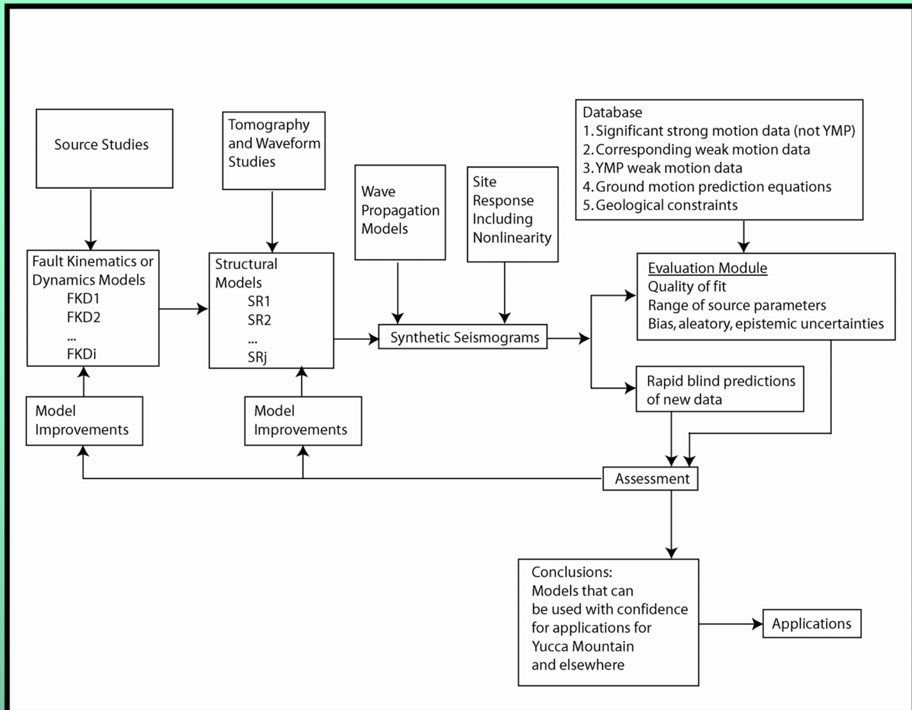
Results

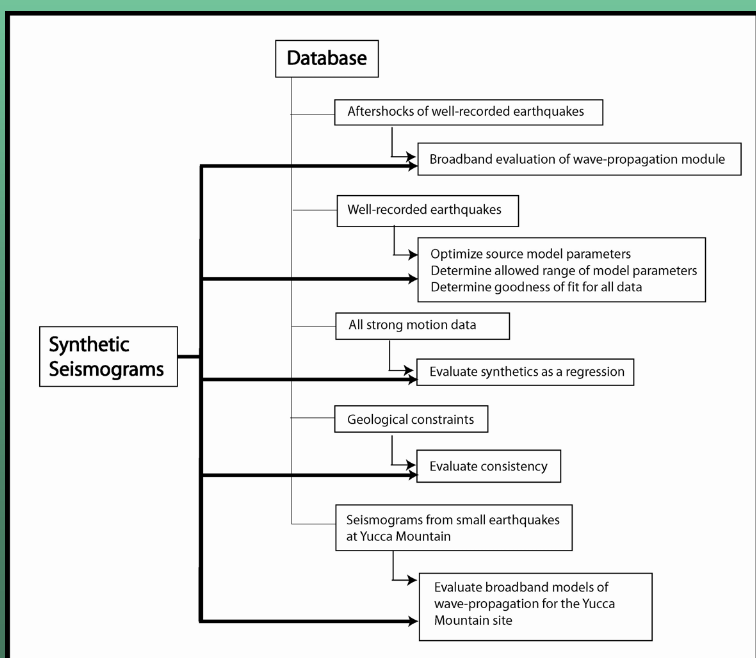
- Convincing evidence that the models are sufficiently reliable for engineering applications.
- Ready to apply to improved probabilistic seismic hazard analysis.

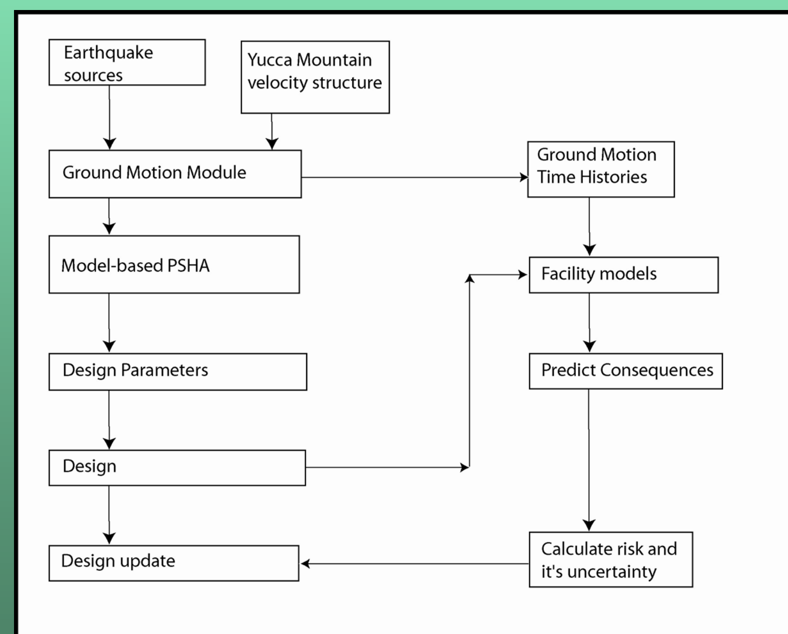

Earthquake sources
Yucca Mountain velocity structure
Ground Motion Module
Ground Motion Time Histories
Model-based PSHA
Facility models
Design Parameters
Predict Consequences
Design
Calculate risk and it's uncertainty
Design update



Combined: an enormous and very sophisticated system

Requires high performance computing.





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Summary

- To achieve this will require teamwork of seismologists, engineers, and computer scientists.
- Challenge: to develop a team that can be sustained for the long run.
  - A national lab may be the best environment.
  - Close involvement of university research community.

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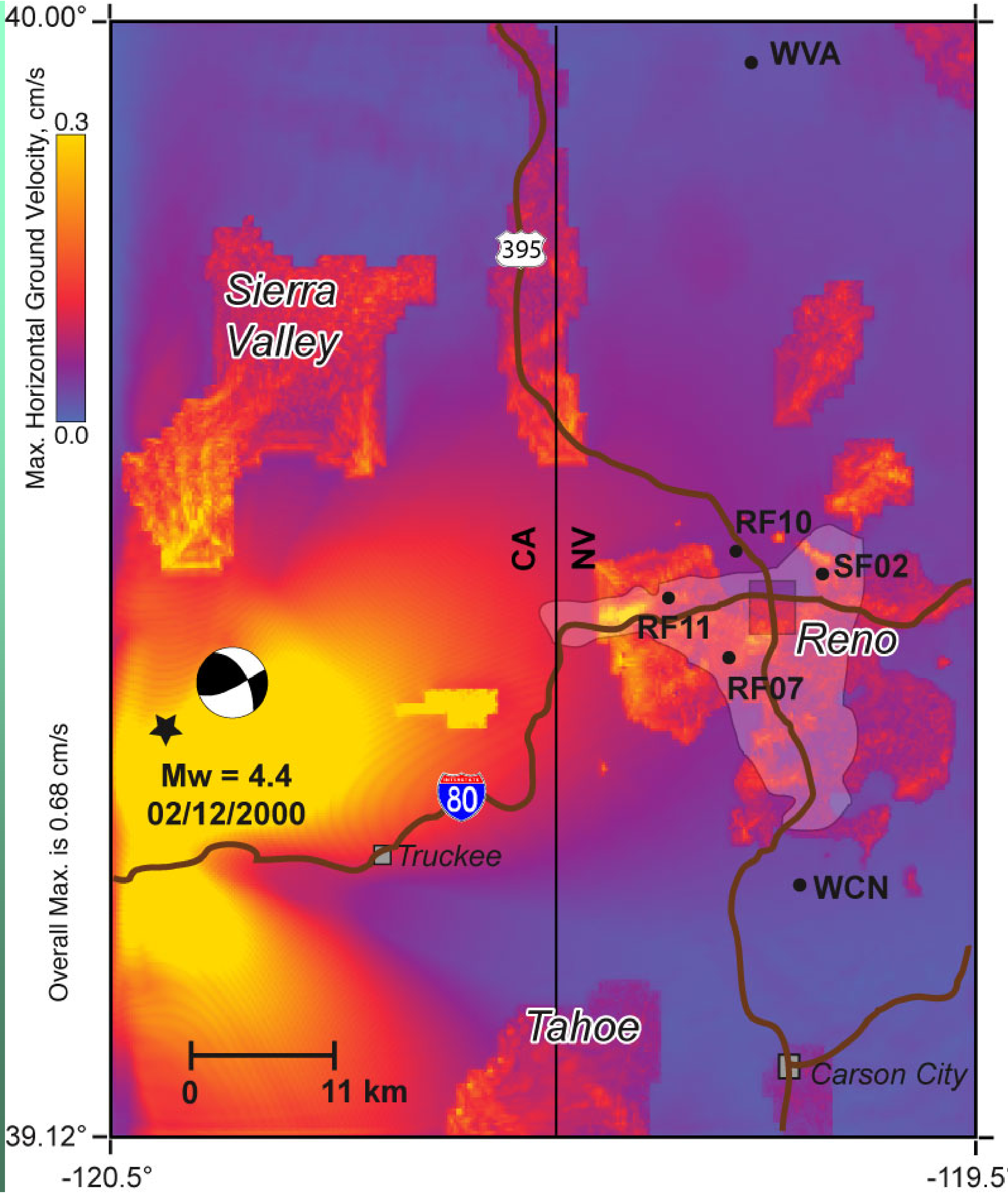
Will Advanced Simulations Really Help?

- Clearly, a system like this will come up with results. Will they be an improvement?
- Need to demonstrate that the simulations achieve a significant reduction in uncertainties through the addition of more physics.
- Some existing simulations suggest why this will be achieved.

Movies

- Reno
  - This movie is prepared by Aasha Pancha and John Louie of the University of Nevada, Reno. The file name is Truckee-3C.mov. The movie was prepared using software e3D written by Shawn Larsen of LLNL.
  - Link from: http://www.seismo.unr.edu/ccog/
  - http://www.seismo.unr.edu/ftp/pub/louie/convimage/Truckee-3C.mov
- Las Vegas
  - This movie is prepared by John Louie of the University of Nevada, Reno. The file name is NTS-LV-2s-3C.mov. The movie was prepared using software e3D written by Shawn Larsen of LLNL. This movie is available from John Louie's web site.
  - Link from: http://www.seismo.unr.edu/hazsurv/
  - http://www.seismo.unr.edu/hazsurv/NTS-LV-2s-3C.mov
- San Andreas NW
  - This movie was prepared by Prof. K. B. Olsen of San Diego State University. It is file nvx.mpg, available from Prof. Olsen's web site.
  - http://www-rohan.sdsu.edu/~kbolsen/terashake.html
- San Andreas SE
  - This movie was prepared by Prof. K. B. Olsen of San Diego State University. It is file svx.mpg, available from Prof. Olsen's web site.
  - http://www-rohan.sdsu.edu/~kbolsen/terashake.html

– Subsequent slides are scenes from these movies.



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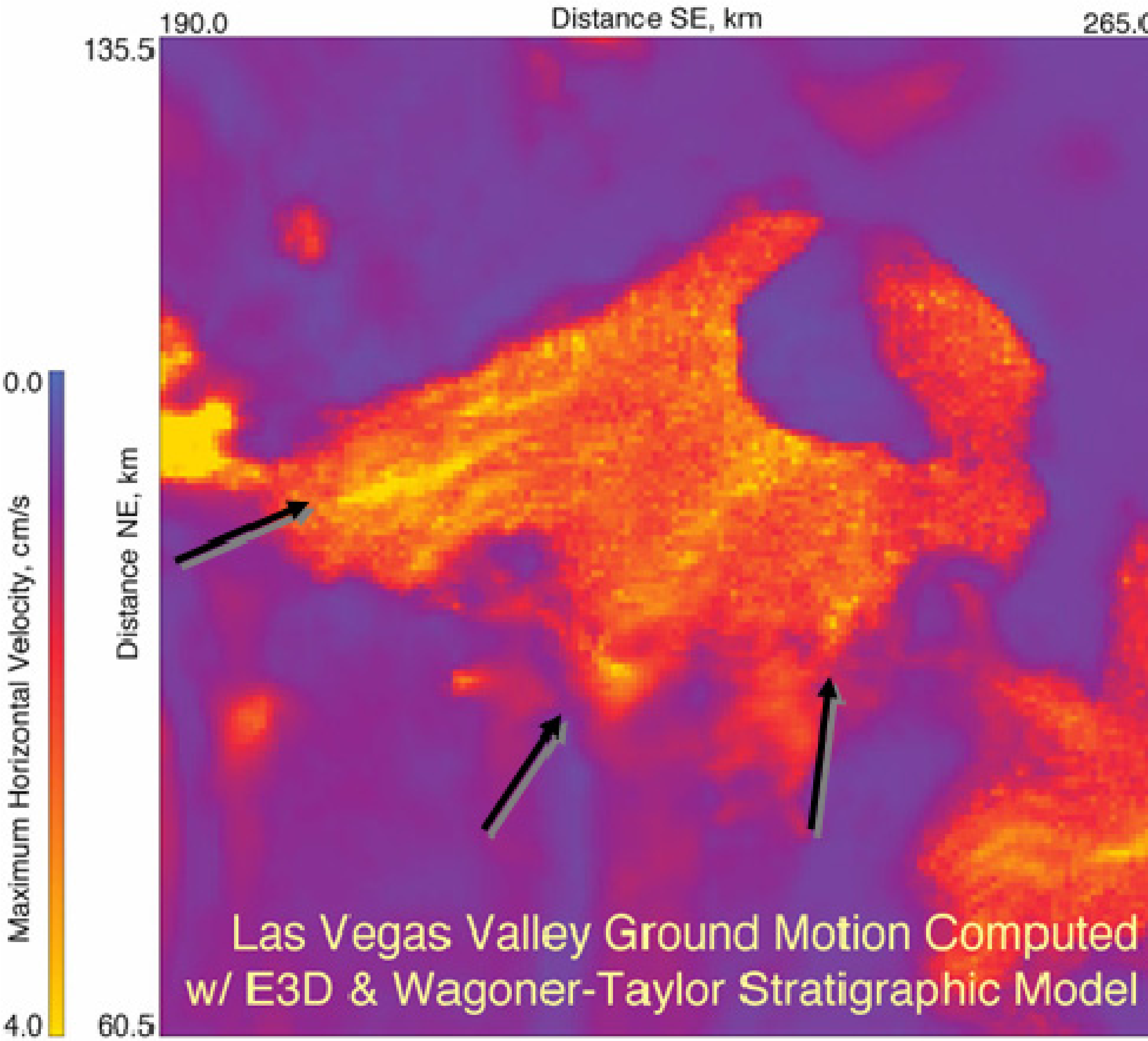

Courtesy:
John Louie

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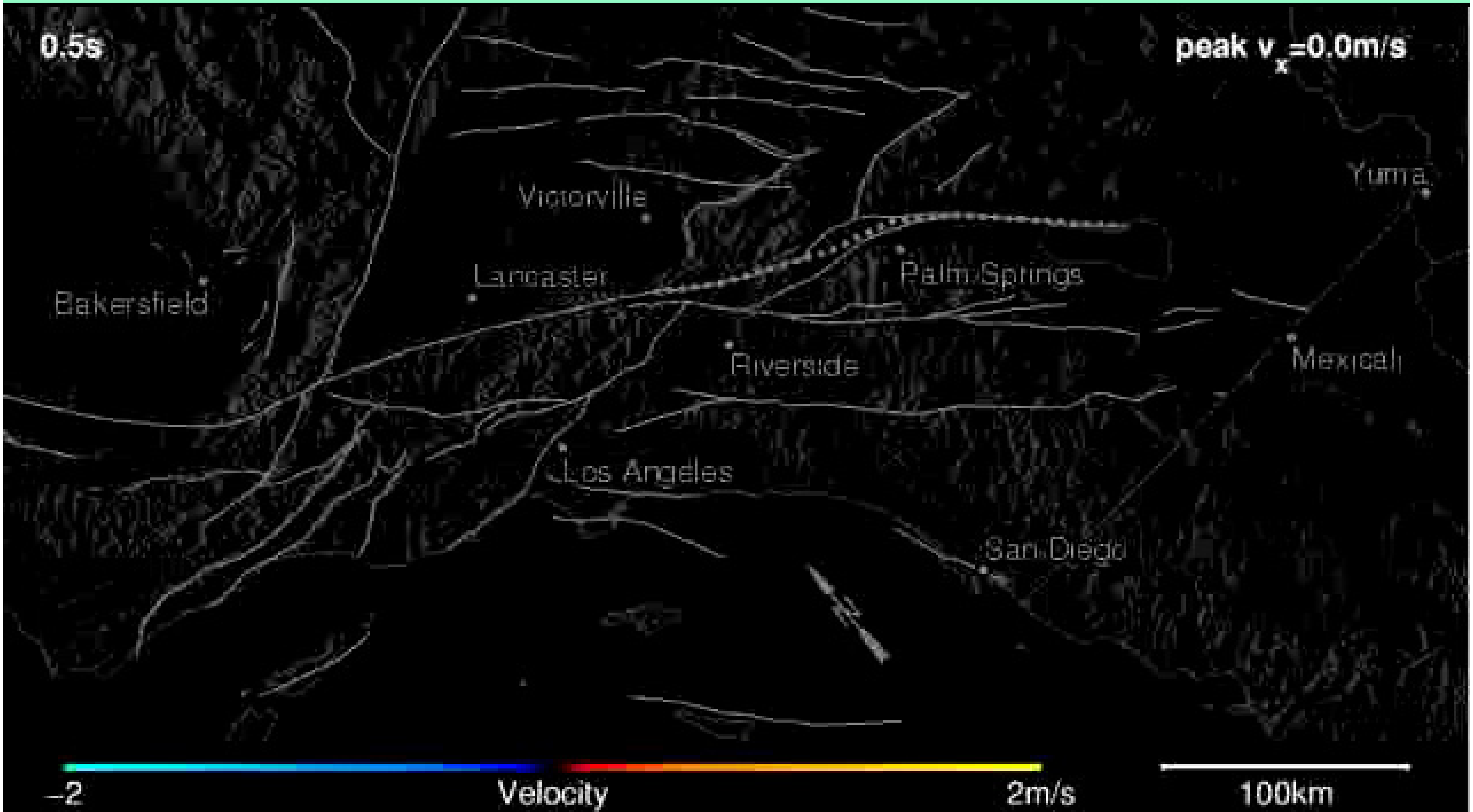
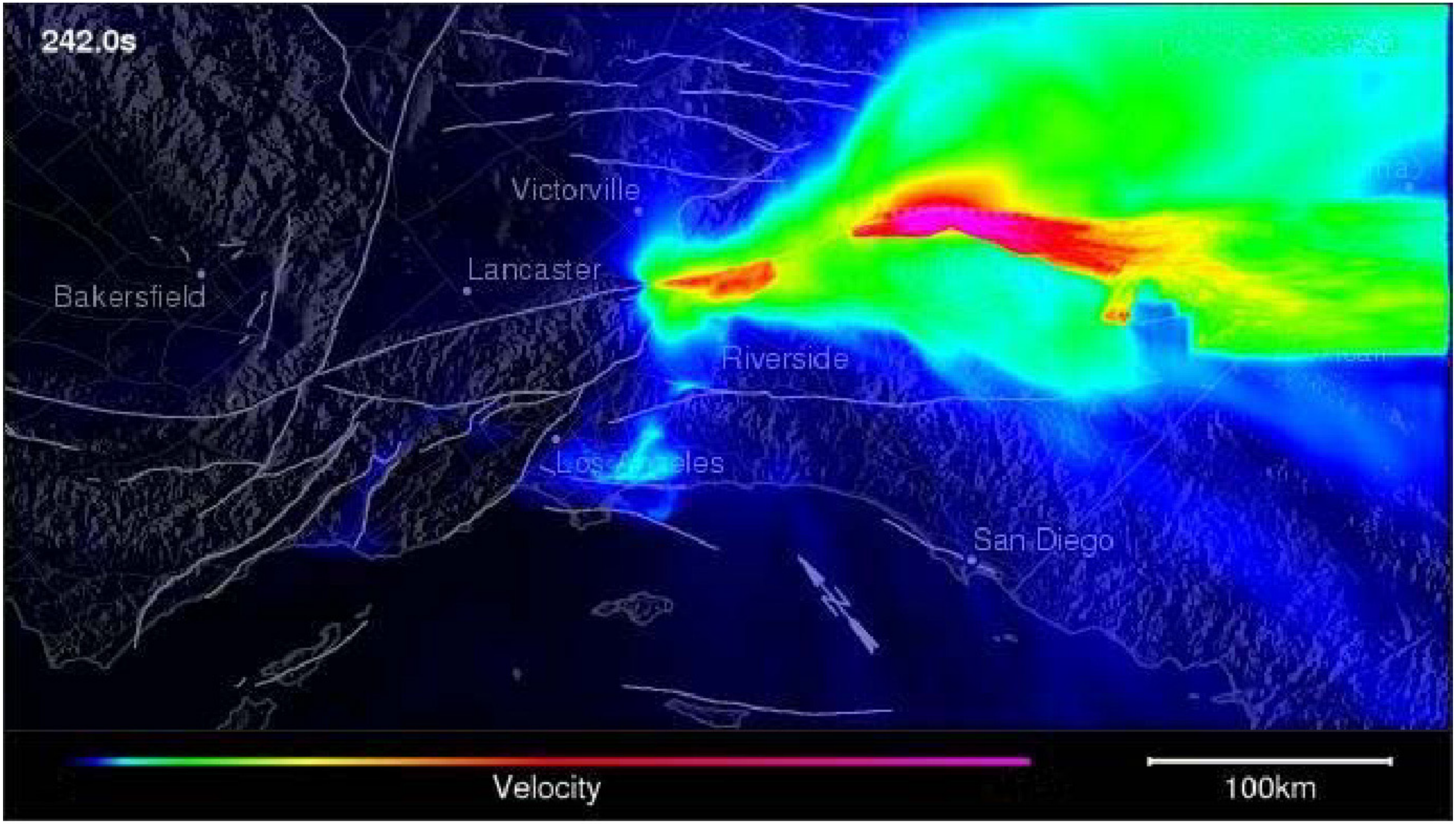
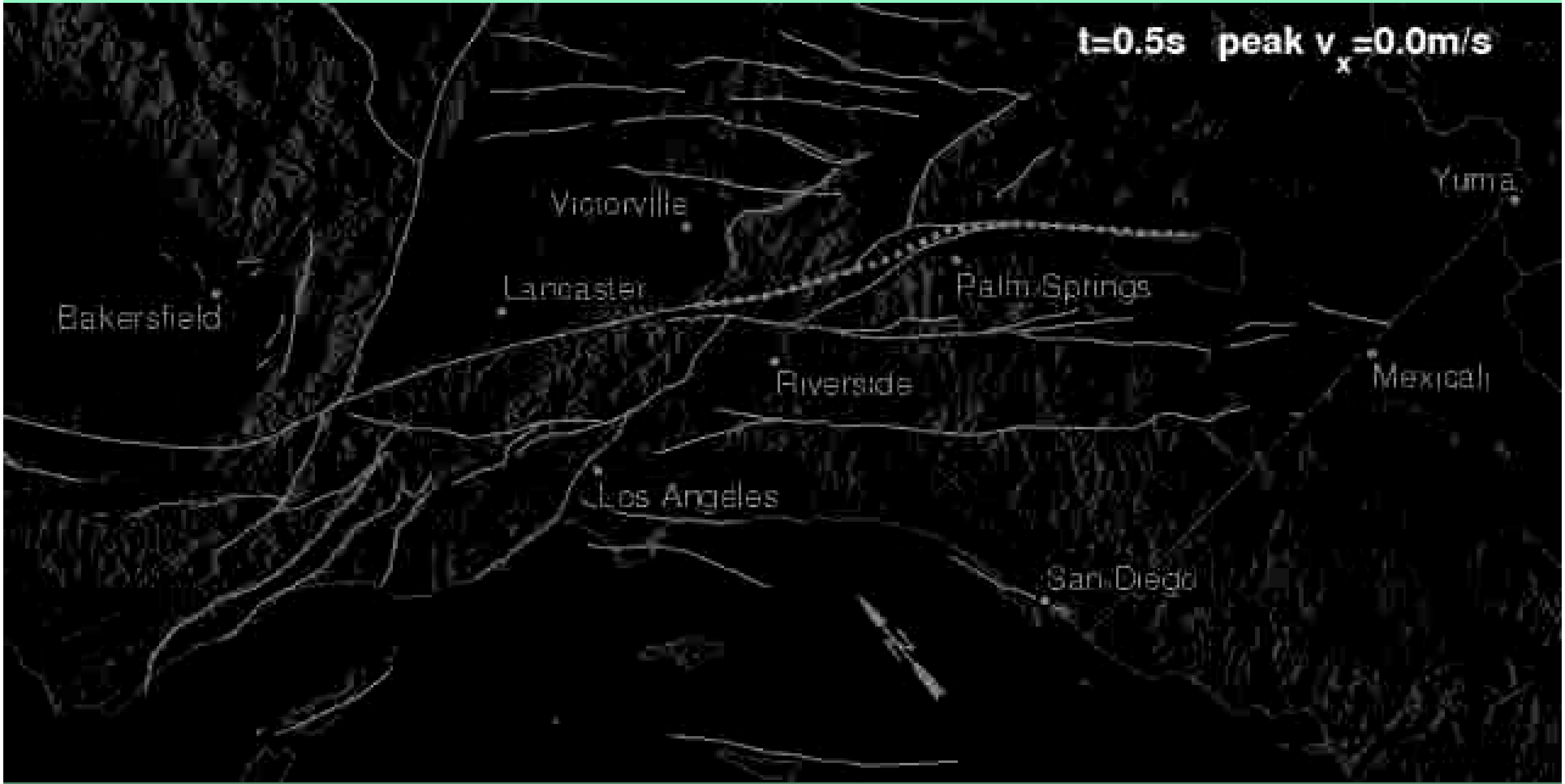

0.5s
peak vx=0.0m/s
Victorville
Yuma
Lancaster
Palm Springs
Bakersfield
Riverside
Mexicali
Los Angeles
San Diego
-2
Velocity
2m/s
100km


242.0s
Victorville
Lancaster
Bakersfield
Riverside
Los Angeles
San Diego
Velocity
100km



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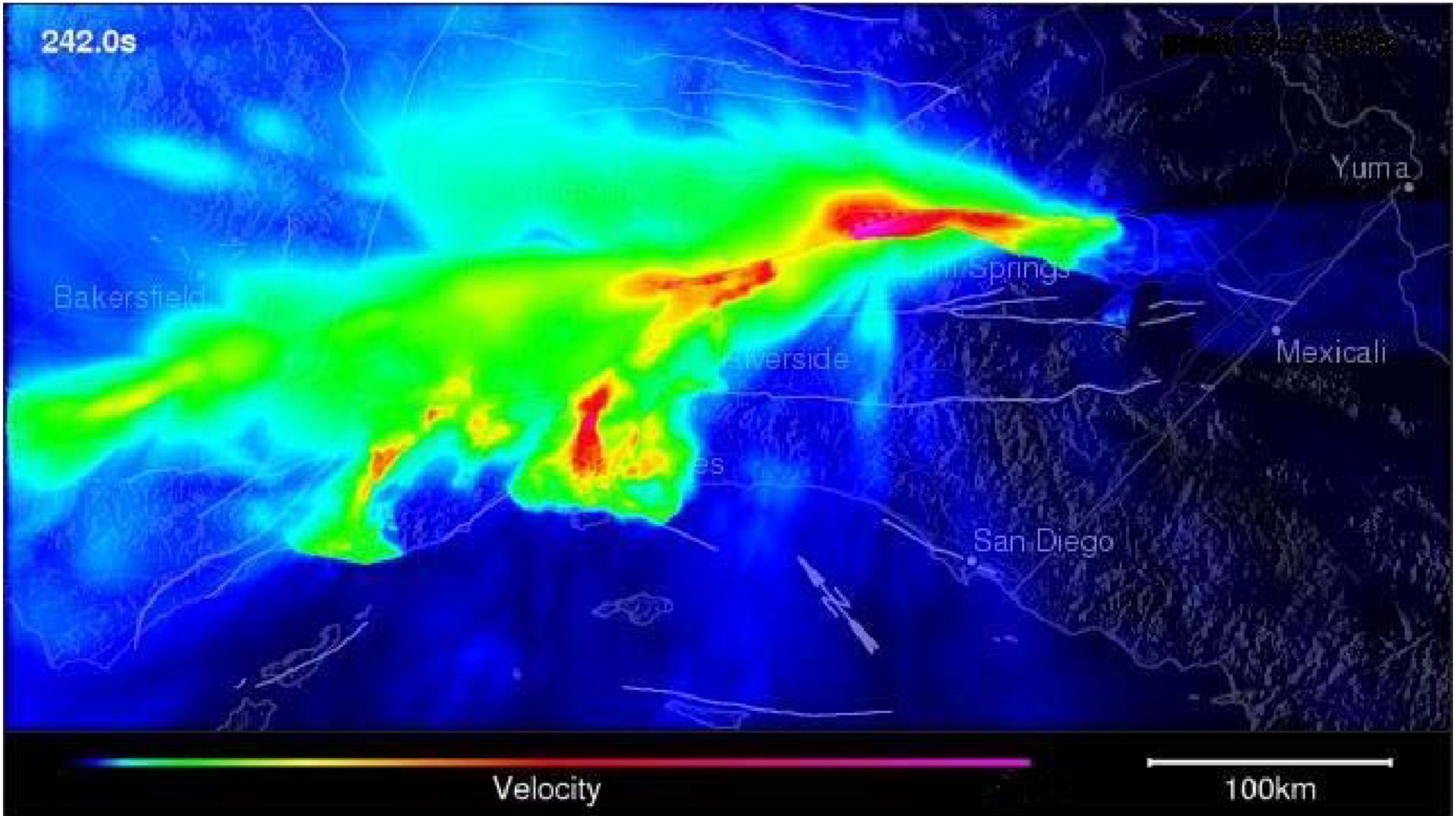

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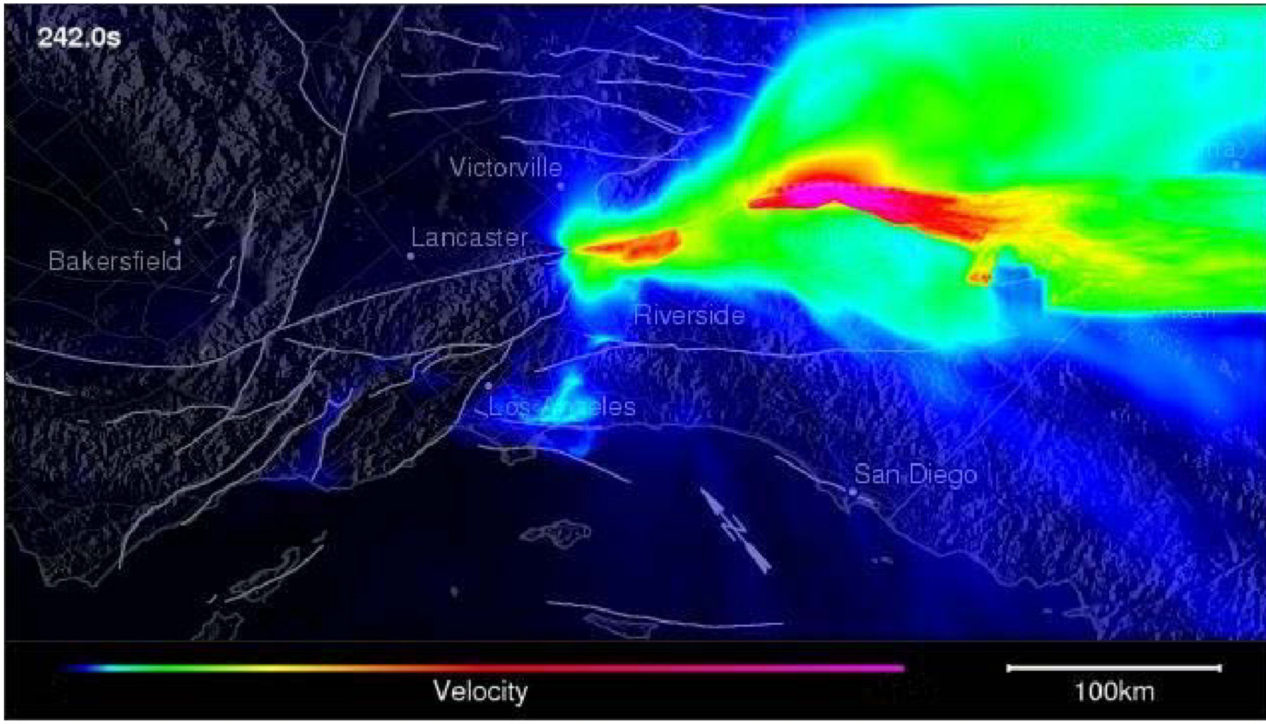
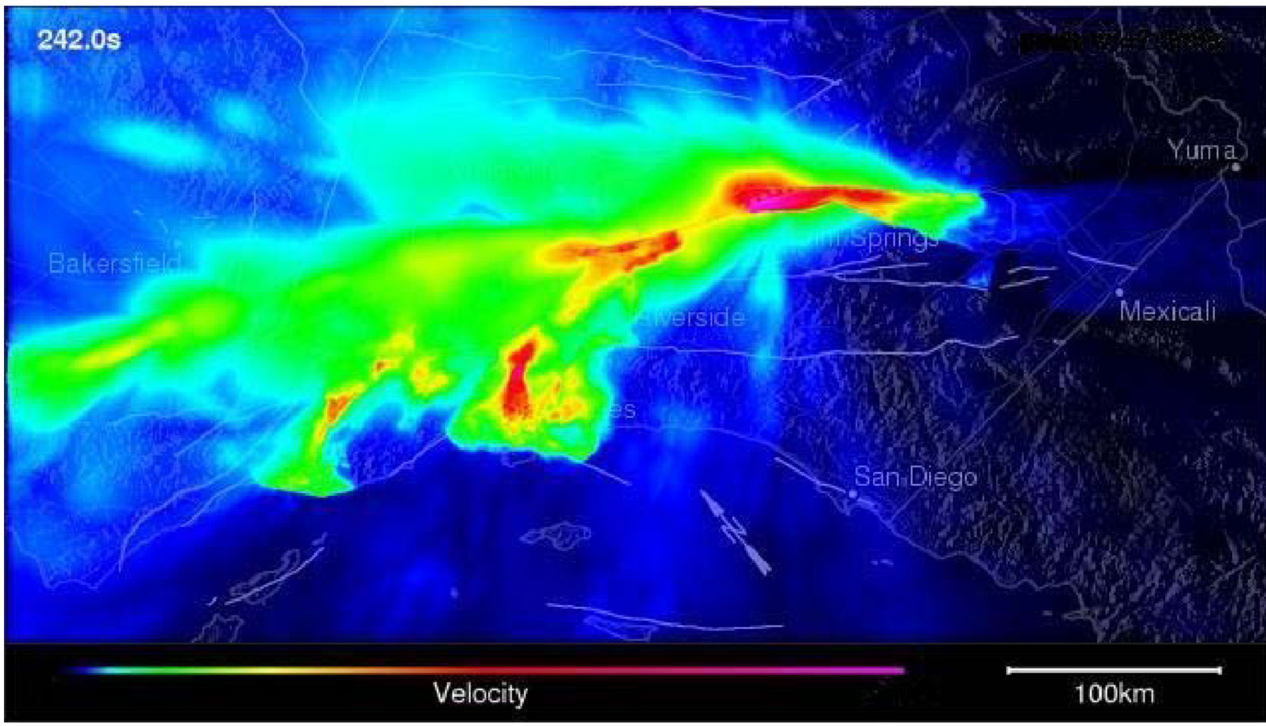


242.0s
Victorville
Lancaster
Bakersfield
Riverside
San Diego
Velocity
100km



242.0s
Yuma
Bakersfield
Mexicali
San Diego
Velocity
100km

Summary

- At a fixed distance from the fault, these models predict a huge variation in amplitude.
- Physical models that recover such variations will have much less uncertainty, and thus will result in more realistic seismic hazard predictions.

Conclusions

- Improving seismic hazards models is a very large problem.
- Requires advanced simulations, sophisticated computational systems, multidisciplinary collaborations

Notes on selected slides:

1. Thank you to Dave McCallen for inviting me to give this talk.
2. Location map for Yucca Mountain. Background is population density. Yucca Mountain is in the lowest category of population density, but there are earthquakes nearby.
3. More details of Yucca Mountain. The air photo on the upper right shows the effect of faulting. The photo is looking towards the south. The west side of Yucca Mountain is controlled by the Solitario Canyon fault. You can see the topographic expression of additional smaller faults east of the Yucca Mountain crest. Conclusion: there is a seismic hazard, and thus a need for a careful seismic hazard analysis.
4. The hazard analysis was carried out by a large team of scientists led by Carl Stepp. The result is published in Stepp et al (Earthquake Spectra).
The probabilistic seismic hazard analysis took the viewpoint that it would try to predict the hazard for the fictitious "Point A". Point A is on the surface, but defined with a high value of Vs and a low value of kappa. Later applications can use more or less standard seismic approaches to convert motions at Point A to other points of interest.
5. This figure does not appear in the Stepp et al article, which was truncated at a higher probability. The PSHA used several "expert opinions" about the input, and calculated hazard curves for each. The statistics of these outputs were examined, and ground motions exceeded by various percentiles are tabulated here. The mean gets higher than the 85th percentile because the mean is taken as the average of annual probability rather than the average of the log of the annual probability.
6. Note the scale, dropping to 10^-8. This comes from the level of regulatory concern, where the probability of exceedance is 10^-4 in 10^4 years.
Note also the horizontal scale, where then mean value reaches over 11 g at the annual probability of 10^-8. This extreme level of ground motion has raised some skepticism, as it is substantially larger than the largest ever observed.
7. This slide adds a compilation of mine of the extreme accelerations that have been observed in the past. Note that all observations are well below the average line at 10^-8 and most of the models. Of course the observations provide a lower bound to what is possible, but at the same time the factor of 5 between the mean and these observations raise questions. Note also that this is in one sense comparing apples and oranges, since the observations can be anyplace worldwide while the hazard curve is a prediction for a specific site in a low-seismicity region.
8. Equivalent for peak velocity. This represents the middle frequencies on the spectrum as well.
9. Mean value goes to 13 m/s, which is again much higher than anything observed. Ground motions greater than the 15th percentile are greater than anything ever observed anyplace in the world.
Additional evidence for problems with the hazard curves. Precarious rocks. Intact rocks.
10. This compares two cliff faces on the Nevada Test Site. At the top left, the face was near an underground nuclear explosion, and has been shattered with large blocks thrown out large distances from the original cliff face. At right, the face is undisturbed. The thick layer of desert varnish indicated that the cliff face has not been disturbed for a very

long time. There is no apparent mega-breccia at the base of the cliff. Photos and interpretation courtesy of Jim Brune.
11. On the left, a road cut in southern California, on the hanging wall of a thrust fault. Half of the observations of extreme velocities shown previously were on the hanging wall of a thrust fault. On the right, a cliff face of 10 Ma old rock on Yucca Mountain, showing none of the shattering. A rough estimate of the strains necessary to shatter the rock on the right is possible. These strains would put an upper bound on ground motions for the lifetime of the rock formation. Preliminary estimates are that these are lower than those predicted by the hazard curve. Photos courtesy of Jim Brune.
12. Whitney rock at Yucca Mountain. Photo courtesy of Jim Brune.
13. Slide courtesy of Matt Purvance, UNR. From Matt's PhD thesis. Require accompanying movies to see. Movies not currently posted on the web.
14. Slide courtesy of Matt Purvance, UNR. From Matt's PhD thesis. Require accompanying movies to see.
15.
16. Go back to basics. Define a hazard curve.
I contend that estimating the hazard curve is equivalent to attempting to predict the result of a physical experiment, as described in this slide.
17. This is an example of executing the experiment. I've been collaborating with Mexicans for many years to run a strong-motion network in Mexico. 20 years of data, now. Location index and site locations.
18. Select one site, at Caleta de Campos. Consider the set of all records from that station – 72 so far. Pick one particular parameter of interest – in this case peak horizontal acceleration. Sort from largest to smallest. The largest value has occurred once in 20 years. Second largest has been equaled or exceeded twice in 20 years. So on. Derive the rate at which peak acceleration has been equaled or exceeded over the last 20 years. From that it's easy to also derive annual probability.
19.
20. This is one source model for western Nevada, taken from the USGS web pages.
21. This is the ground motion prediction equation by Abrahamson & Silva.
Combine the last two slides to come up with a model for where earthquakes happen and how often.
22. Left, again, Abrahamson and Silva (1997) model for ground motion predictions. Right, my figure. Factor of 28 is an estimate from the slide, and not exact. Mainly it gives the idea that the uncertainties multiply ground motion a lot.
23. Left, again, Abrahamson and Silva (1997) model for ground motion predictions. Right, my figure. Sigma=0.43 not checked from numerical value but estimated from the figure. Factor of 5.5 is an estimate from the slide, and not exact. Mainly it gives the idea that the uncertainties multiply ground motion by about this much.
24.
25. I think the concept was around well before SCEC gave it this name. This differs from the SCEC literature by adding in the Source Model box. I think it's essential, and implicit in what they do, but we need to explicitly deal with in in the project I'm describing.
26. Physical starting point for prediction of ground motions.
27. A source model that gives the right amount of complexity including at high frequencies.

28. Major phenomena of wave propagation in flat layered structure. UNR approach by Yuehua Zeng (innovated for scattering, source radiation, and shallow layer complexity), Yu Guang (using layered model only), John Anderson. The computer code we use was written by Yuehua Zeng including the layered model.
29. Show examples for two events, M6 in 1990, M8 in 1985. From MS thesis at UNR by Mandy Johnson
30. M6. From MS thesis at UNR by Mandy Johnson
31. M8.1 From MS thesis at UNR by Mandy Johnson.
32. Synthetics for a site in India. Just one example of the variability. From our paper on the Uttarkashi, India, earthquake.
33. Start a discussion on how one could use advanced simulations to make progress on the problem.
This is a proposal that in part, we at UNR submitted to NSF 2-3 years ago. It's been enhanced and combined with a collaboration with LLNL (Bill Foxall, Jean Savy, Larry Hutchings), since one of our weakensses was on the advanced computing. They added the application to PSHA.
34. Simplified from the 2004 proposal, for clarity in this presentation.
35. Source studies. Every package of studies requires teamwork. This field is an excellent one for university involvement, since there are several groups of scientists trying to understand the kinematics and dynamics of the earthquake source. Needs workshops, coordination. Each team needs this system to test their source models against real data.
36. Model by Matt Purvance at UNR, in collaboration with Peter Cundle. Particle model showing regions of compression and extension due to asperities on a fault, as the stress builds up towards failure.
37.
38.
39.
40. Point out LLNL contribution. Shawn Larsen wrote E3D, which we are using in collaboration. Point out grand challenge to invert complete seismograms from small earthquakes to improve model of the Earth structure.
41.
42.
43.
44. Next slide explains how these work together, and identifies different kinds of predictions, calibrations, validations.
45. Top two used for calibration. Application to all strong motion data validates model.
46.
47. Emphasis here is that the blind predictions for new earthquakes will do more than anything else to build confidence in the system.
48.
49.
50.
51. With this, ready to go on to applications.
52.

53. Note that the vertical line on the left is the equivalent to current PSHA. Added value of this approach is the synthetic seismograms which can be used for a more effective link to subsequent analysis.
54.
55.
56.
57. Reno movie (outside file) generated by Aasha Pancha (UNR) with help moviemaking from John Louie. Uses E3D, LLNL code by Shawn Larsen. Las Vegas movie by Shawn Larsen.
58. Figure by John Louie, peak values from the Reno movie. This movie is prepared by Aasha Pancha and John Louie of the University of Nevada, Reno. The file name is Truckee-3C.mov. The movie was prepared using software e3D written by Shawn Larsen of LLNL.
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59. Figure by John Louie, peak values from the Las Vegas movie. This movie is prepared by John Louie of the University of Nevada, Reno. The file name is NTS-LV-2s-3C.mov. The movie was prepared using software e3D written by Shawn Larsen of LLNL. This movie is available from John Louie's web site.
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61. Figure is from SCEC annual report for 2004, SCEC web site.
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63. Figure is from SCEC annual report for 2004, SCEC web site.
64. Figure is from SCEC annual report for 2004, SCEC web site.
Note here and in all four movies how a series of points equidistant from the fault would have a large range of peak values. Graphic picture of how the large value of sigma might arise in ground motion prediction equations.
65.
66.